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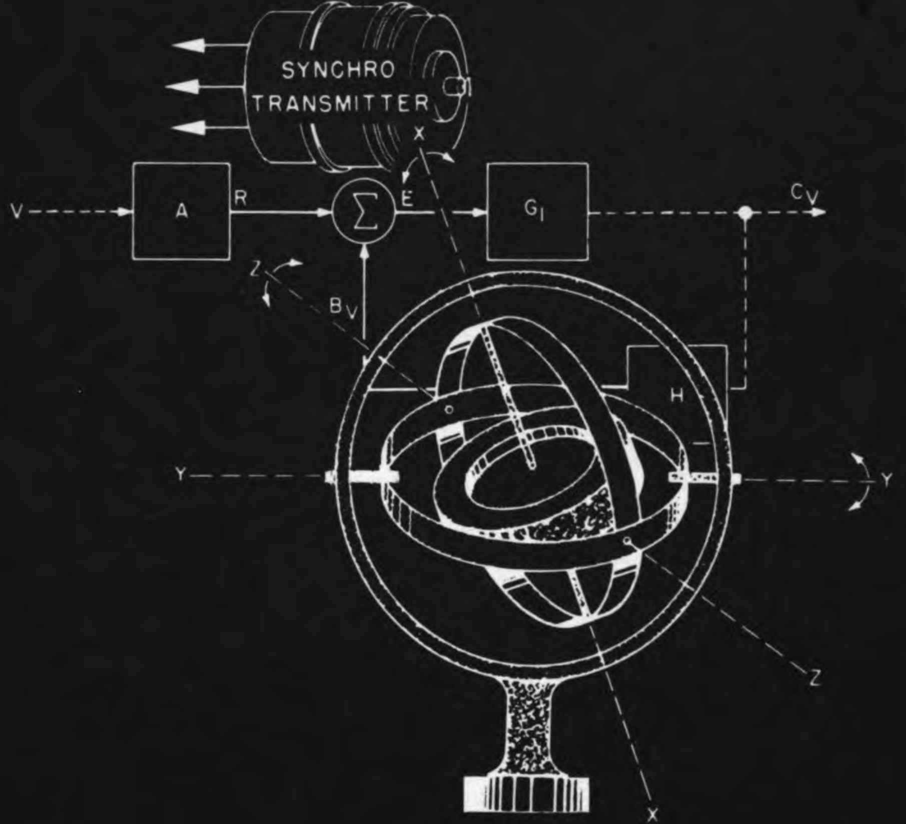

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MAR 5 1971

SYNCHRO, SERVO AND GYRO FUNDAMENTALS

MAR 5 1971
UNIVERSITY OF CALIFORNIA

BUREAU OF NAVAL PERSONNEL

RATE TRAINING MANUAL **NAVPERS 10105**

PREFACE

This manual is written for men of the U.S. Navy and Naval Reserve whose duties require them to have a knowledge of servosystems and associated devices.

As one of the basic rate training manuals, this manual was prepared by the Training Publications Division, Naval Personnel Program Support Activity, Washington, D.C., for the Bureau of Naval Personnel. Technical assistance was provided by the Navy Training Publications Center, Naval Air Station, Memphis, Millington, Tennessee.

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THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

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CHAPTER 1

INTRODUCTION

This manual is intended as a basic training manual for men of the Navy and Naval Reserve whose duties require them to have a knowledge of servosystems and associated devices. It is assumed that the student studying this manual is familiar with the contents of Basic Electricity, NavPers 10086 (revised) and those portions of Basic Electronics, NavPers 10087 (revised) dealing with the theory of electron tubes, semiconductor devices, power supplies, and amplifiers.

Chapters 2 and 3 of this training manual discuss Navy synchro units. Chapter 2 describes the general construction of the units, explains how they are classified and marked, and discusses the basic principles upon which they operate. Chapter 3 presents information relating to multi-speed units, standard connections, and zeroing procedures. This chapter also includes material concerning other units similar to synchros, such as IC synchros, resolvers, and step-by-step units.

Chapter 4 discusses the operation and applications of servosystems. The basic open and closed loop systems are described, and the various types of error detectors and servoamplifiers used with the systems are discussed.

Gyroscopic principles, and the common types of gyro units used in the Navy are discussed in chapter 5. Also included in this chapter is a discussion on the basic types of accelerometers used in shipboard and aircraft systems.

Chapter 6 presents a basic functional description of some of the shipboard and aircraft systems that utilize the various types of components discussed in this training manual.

Appendix I includes synchro trouble information.

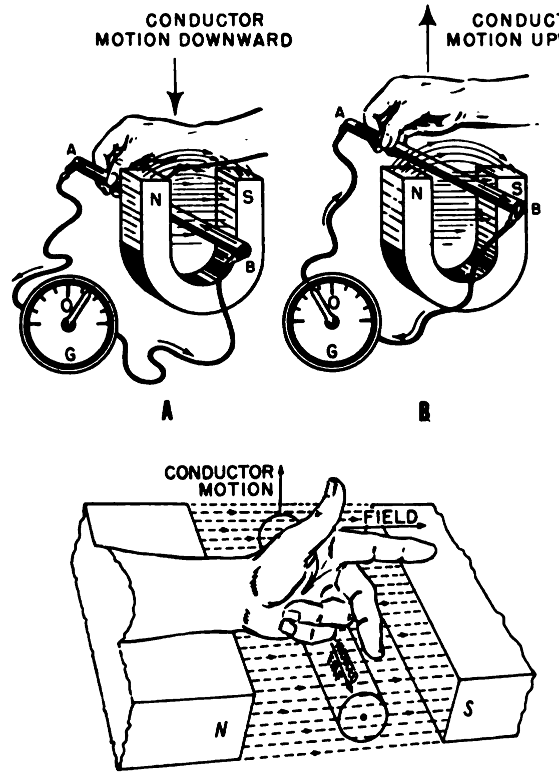
The remainder of this chapter reviews and amplifies some of the basic concepts of electromagnetic induction, as discussed in Basic Electricity, NavPers 10086 (revised), and then discusses the common types of motors and generators used in connection with servosystems. The theory of operation of these units, and how they differ from conventional motors and generators is presented in this chapter; how they function in a servosystem is discussed in later chapters.

ELECTROMAGNETIC INDUCTION

Electromagnetic induction has been defined as the process of producing a magnetic effect by electrical means, or an electrical effect by magnetic means, without physical contact. In 1819 Hans Christan Orsted, a Danish physicist, discovered that a wire carrying an electric current affected a compass needle, and was thus itself a kind of magnet. It was not until 12 years later, however, that Michael Faraday in England and Joseph Henry in America were able to prove that a magnet could be used to produce an electric current. This principle is described in the following paragraphs.

If the ends of a conductor are connected to a low-reading voltmeter or galvanometer and the conductor is moved rapidly down through a strong magnetic field, as illustrated in figure 1-1A, there is a momentary reading on the meter. When the conductor is moved up through the field (fig. 1-1B), the meter deflects in the opposite direction. If the conductor is held stationary and the magnet is moved so that the field cuts across the conductor, the meter is again deflected in the same manner as when the conductor was moved and the field was stationary. If the conductor is moved in the field in a sidewise direction, from the North Pole to the South Pole of the magnet, or vice versa, so that no lines of force are cut, the meter will not be deflected.

The voltage developed across terminals AB of the conductor (fig. 1-1A and 1-1B) by electromagnetic induction is known as an induced electromotive force (e.m.f.) and the current that flows as a result of this e.m.f. is known as an induced current. This is a definite relation between the direction of flux, the direction of motion of the conductor, and the direction of the



LEFT-HAND GENERATOR RULE
C

12.143
Figure 1-1.—Voltage produced by magnetism.

induced e.m.f. as shown by the left-hand generator rule (fig. 1-1C).

From the preceding paragraphs, it can be seen that for an e.m.f. to be induced in a conductor by electromagnetic induction, there must be relative motion between the conductor and the magnetic field, and this motion must be in such a manner as to have the conductor cut the lines of force (flux) of the field. The magnitude of this induced e.m.f. is proportional to the rate at which the conductor cuts the lines of force. This will be remembered as Faraday's law from Basic Electricity, NavPers 10086 (revised). In addition, the magnetic field created by the induced current opposes any change in the original magnetic field responsible for the induced e.m.f. This is known as Lenz's law and is also discussed in detail in Basic Electricity, NavPers 10086 (revised).

SELF AND MUTUAL INDUCTION

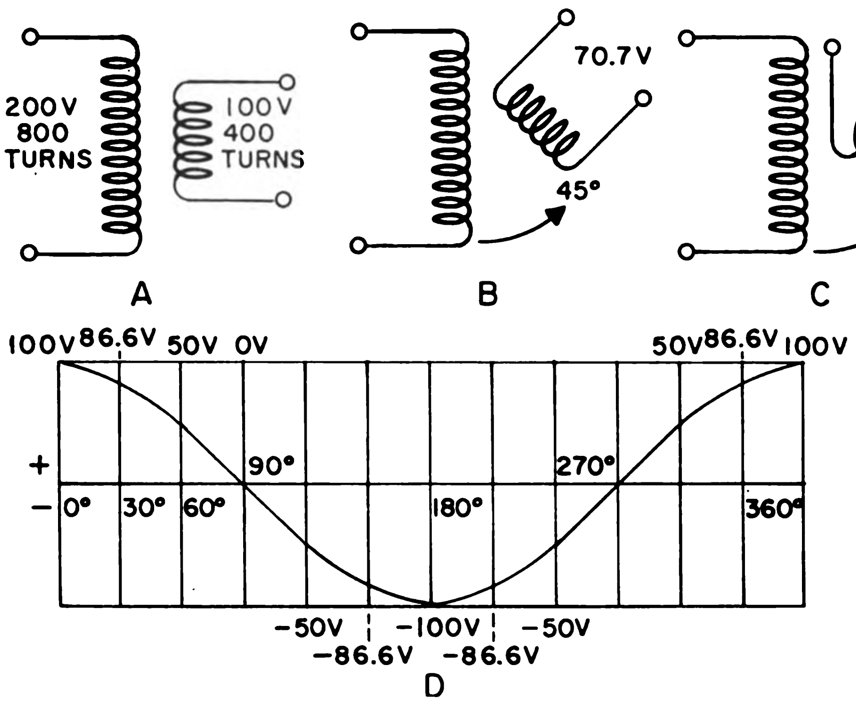
All current-carrying conductors are encircle by magnetic lines of force that vary directl with the current within the conductor. Any chang to the current flow through the conductor bring about a corresponding change in the magneti field around the conductor. If the current rise and falls, the magnetic field will expand an collapse accordingly, and thus induce an e.m.f within the conductor. This is called "self induction." The e.m.f., due to self induction, is always in opposition to the applied e.m.f. (Lenz's law) and is known as a counter electromotiv force (c.e.m.f.).

The changing magnetic field around a current-carrying conductor will, in addition to inducing an e.m.f. within the conductor itself, induce an e.m.f. in any nearby conductor, or conductors, within the magnetic field. This is called "mutual induction."

TRANSFORMER ACTION

The operation of the transformer is based upon the principle that electrical energy can be transferred by mutual induction from one winding to another. As explained in Basic Electricity, NavPers 10086 (revised), the voltage transformation from the primary to the secondary winding of a transformer (disregarding the small internal losses within the transformer), is proportional to the turns ratio of the windings as shown in figure 1-2A. This is true as long as the primary and secondary windings are physically arranged (with their axes parallel, as in fig. 1-2A) so that there is maximum magnetic coupling between the windings. With the windings so positioned, maximum magnetic lines of force from the primary winding cut the maximum number of turns of the secondary winding, thus, inducing maximum voltage in the secondary. This is the normal arrangement for conventional transformers.

If the position of the primary or secondary winding of a transformer is changed so that the axes of the windings are no longer parallel, the magnetic coupling between the windings will be decreased resulting in a decrease in the voltage induced in the secondary winding. Increasing the angle of displacement between the windings up to 90° will cause a continuing decrease to zero in the secondary voltage (fig. 1-2A and B). (When the windings are displaced 90°, they are at right angles to each other, the magnetic lines of force of the primary are not



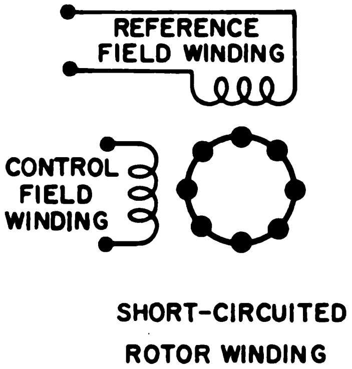
72.40:.41(175)
Figure 1-2.—Transformer action.

cutting the turns of the secondary winding, and thus no voltage is induced in the secondary winding.) The secondary voltage varies as the cosine of the angle of displacement between the windings as shown in figure 1-2D. Synchro units operate on this principle as will be seen in the next chapter.

SERVOMOTORS

Both a.c. and d.c. motors are used in servosystems depending upon the requirements of the system. Systems required to position heavy loads with a wide speed range use d.c. motors, whereas the light loaded and fairly constant speed systems use a.c. motors.

The most common type of a.c. servomotor is the 2-phase induction motor. This motor has a reference (fixed) field, and a control (variable) field spaced 90 electrical degrees apart as shown in figure 1-3. The rotor is usually of the squirrel-cage type, however, other types are sometimes used.



55.39(175)
Figure 1-3.—2-Phase a.c. servomotor.

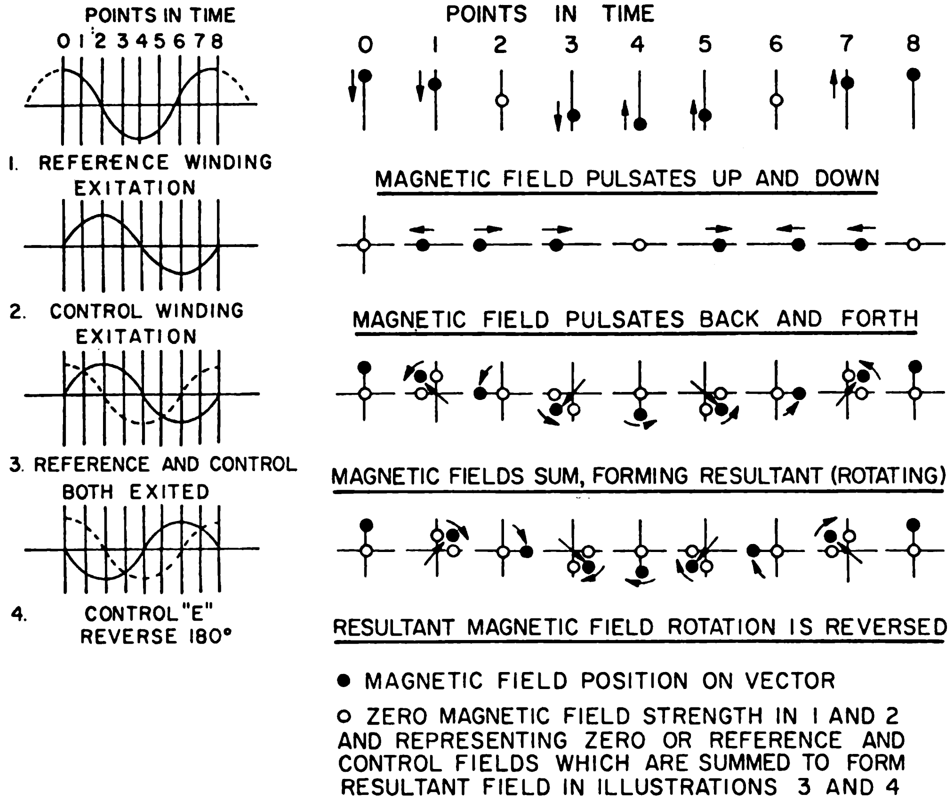
If two a.c. supply voltages 90° out of phase with each other are applied to the reference and control fields (fig. 1-3), the currents in the fields flowing as a result of the applied voltages will also be 90° out of phase with each other;

and since the magnetic fields produced by the currents will be in phase with currents producing them, the magnetic fields will be 90° displaced from each other. These magnetic fields will add vectorially to produce a resultant rotating field as shown in figure 1-4. The rotating magnetic field induces voltages in the rotor causing the rotor to rotate in the direction of the magnetic field as a conventional induction motor.

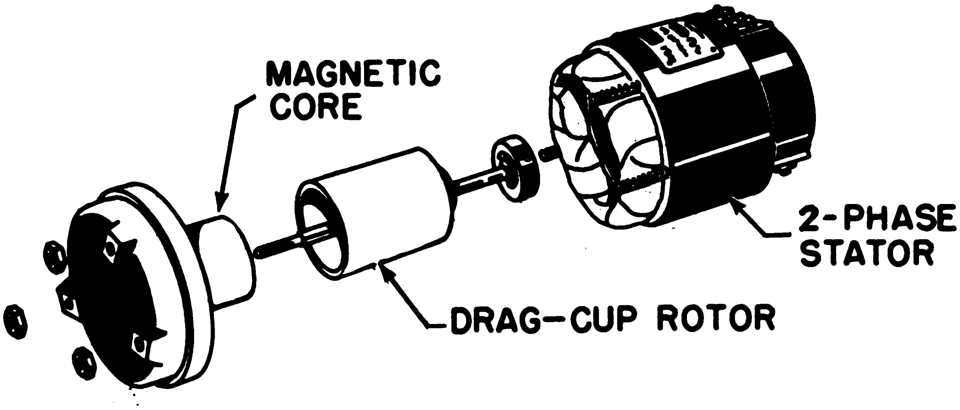
The direction of rotation of the 2-phase servomotor depends upon the phase of the control field voltage (which either leads or lags the reference voltage by 90°), as shown by figure 1-4. Varying the magnitude of the current in either the control or reference field will vary the motor torque. In addition, if either field is deenergized, there will no longer be a rotating magnetic field established and the motor will stop. In actual practice in a servosystem, the reference field is supplied from a constant voltage source and the control field is supplied from the output of a servoamplifier. Thus, the motor speed and direction is controlled by th servoamplifier output, as discussed in chapte 4.

Split-phase a.c. motors are used as servo motors in some applications. The capacitor-ru type discussed in Basic Electricity, NavPer 10086 (revised) is the type generally used Reversal and control are accomplished in th same manner as for the 2-phase induction motor. Other types of a.c. motors used as servomotor in certain applications, which are also discusse in Basic Electricity, NavPers 10086 (revised), are the shaded pole, salient pole, and universa motors.

Another type of a.c. servomotor which is used in very low power applications is the drag-cu servomotor. This motor has a 2-phase (reference and control) stator winding similar to the typ shown in figure 1-3. The rotor, however, consists of a thin aluminum or copper cup, wit the rotor flux being carried by a stationar magnetic core as shown in figure 1-5.


POINTS IN TIME
0 1 2 3 4 5 6 7 8
1. REFERENCE WINDING EXITATION
2. CONTROL WINDING EXITATION
3. REFERENCE AND CONTROL BOTH EXITED
4. CONTROL "E" REVERSE 180°
POINTS IN TIME
0 1 2 3 4 5 6 7 8
MAGNETIC FIELD PULSATES UP AND DOWN
MAGNETIC FIELD PULSATES BACK AND FORTH
MAGNETIC FIELDS SUM, FORMING RESULTANT (ROTATING)
RESULTANT MAGNETIC FIELD ROTATION IS REVERSED
● MAGNETIC FIELD POSITION ON VECTOR
○ ZERO MAGNETIC FIELD STRENGTH IN 1 AND 2 AND REPRESENTING ZERO OR REFERENCE AND CONTROL FIELDS WHICH ARE SUMMED TO FORM RESULTANT FIELD IN ILLUSTRATIONS 3 AND 4

175.1
Figure 1-4.—Reference and control field winding excitation and magnetic field vectors.



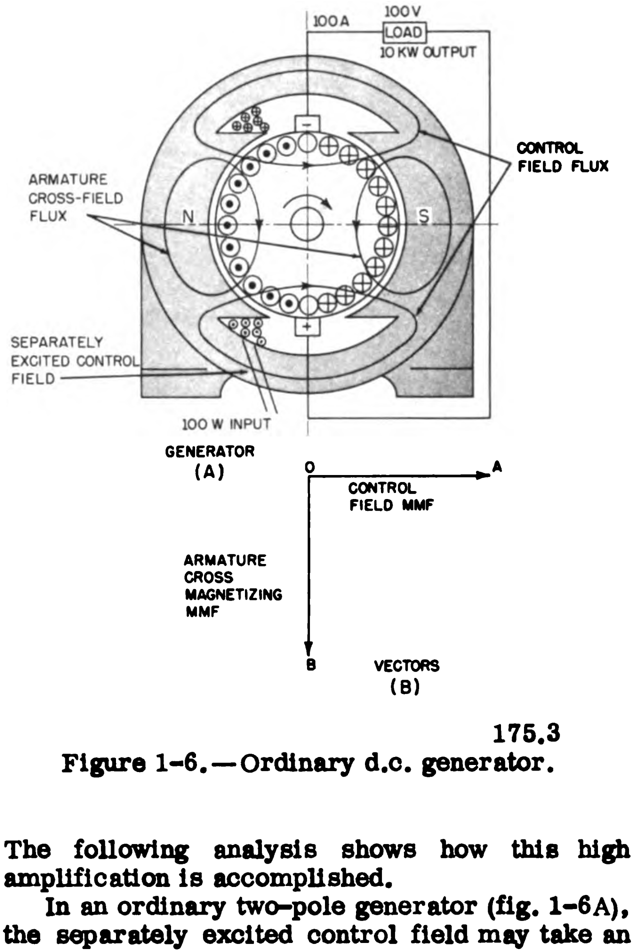
175.2
Figure 1-5.—Drag-cup servomotor.

Direct current servomotors include the series and shunt types. They may be either field or armature controlled. Field control is accomplished by the use of a split field (one field for each direction of rotation), or in some applications, a relay or switching system that reverses the polarity of the field. In certain servo applications, a permanent magnet fixed-excitation type of shunt motor is used. In this case, armature control is used as the field is supplied by a permanent magnet. The shunt motor is the most common type of d.c. servomotor, as it has good speed regulation and starting torque, and when field control is used, it requires very little control power.

Control current for d.c. servomotors is generally supplied by a servoamplifier, the same as a.c. servomotors. Amplidyne generators are used to furnish the control power in some systems; especially systems with heavy loads. A discussion of the amplidyne generator follows.

AMPLIDYNE GENERATORS

The amplidyne generator is a separately excited d.c. generator having a control field that requires a very low power input. The armature output may be as high as 100 volts and 100 amperes, giving an output power of 10 kw. The amplidyne is a control device that is extremely sensitive. For example, an increase in control field power from 0 to 1 watt can cause the generator output power to increase from 0 to 10 kw. It is thus a power amplifier that increases the power by an amplification factor of 10,000.



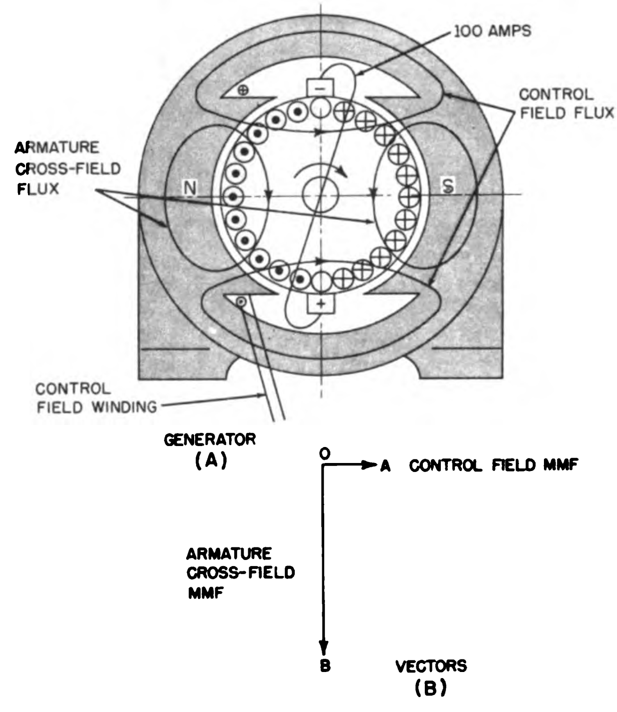
175.3
Figure 1-6.—Ordinary d.c. generator.

The following analysis shows how this high amplification is accomplished.

In an ordinary two-pole generator (fig. 1-6A), the separately excited control field may take an input power of 100 watts in order to establish normal magnetism in the field poles and a normal armature voltage of 100 volts. When this voltage is impressed on a 1-ohm load, the armature will deliver 100 amperes, or an output power of 10 kw. The circles with dots represent armature conductors carrying current toward the observer; those with crosses represent electron flow away from the observer. The control field winding develops a north pole (N) on the left-hand field pole and a south pole (S) on the right-hand field pole.

The relative strength of the control field magnetomotive force (m.m.f.) is represented by vector OA (fig. 1-6B). The armature acting as an electromagnet establishes a quadrature, or cross, magnetomotive force having an axis that coincides with that of the brushes. The relative strength and position of this armature cross magnetizing force is indicated by vector OB. It is about the same length as the control field vector, OA, and is perpendicular to it.

If the strength of the control field is reduced to 1 percent of normal, the armature-generated voltage will fall to 1 percent of normal, or to about 1 volt in this example. The output current from the armature will fall to 1 ampere through the 1-ohm load.



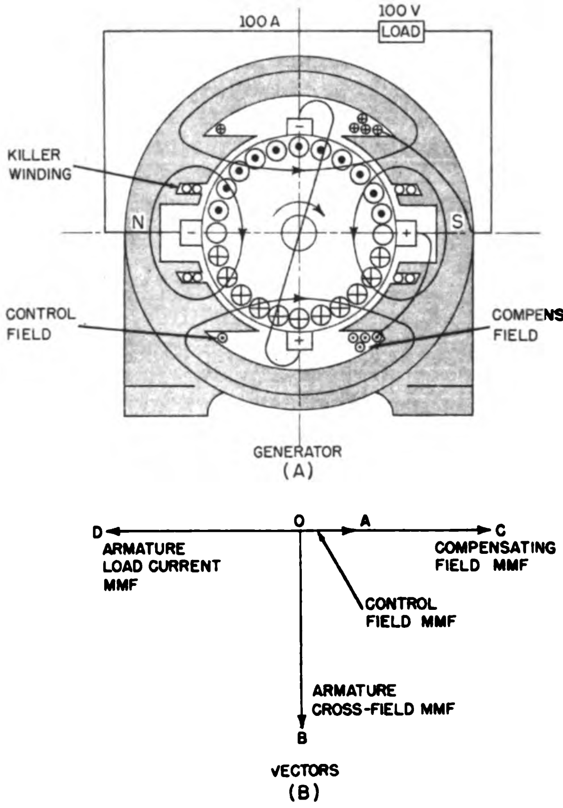
175.4

Figure 1-7.—Generator with short-circuited brushes.

Normal armature current may be restored by short-circuiting the brushes, as shown in figure 1-7A. One volt acting through an internal armature resistance of 0.01 ohm will circulate 100 amperes between the brushes. The control field strength is still 1 percent of its normal value (vector OA fig. 1-7B), but the armature crossfield m.m.f. has been restored to its normal value. as indicated by vector OB.

The armature crossfield is cut by the armature conductors and may be regarded as being responsible for normal load voltage, which is obtained across an additional pair of brushes in the amplidyne generator (fig. 1-8). The axis of these brushes is perpendicular to that of the shorted brushes. The load is connected in series with these new brushes and a compensating winding.

Armature load current is toward the observer around the upper half of the armature windings and away from the observer around the lower half. The armature acts like an electromagnet,



175.5

Figure 1-8.—Amplidyne generator.

which creates an m.m.f. in opposition to the control field m.m.f. and in the same axis as that of the control field (fig. 1-8).

The purpose of the compensating winding is to create an opposing m.m.f. along this same axis to counterbalance the armature load current m.m.f. This counterbalance is made automatic for any degree of load by connecting the compensating winding in series with the load brushes and the load. Vector OC (fig. 1-8), represent the relative magnitude and direction of the compensating winding m.m.f. with respect to the control field m.m.f. (OA) the armature load current m.m.f. (OD), and the armature crossfield m.m.f. (OB).

The main field poles are shown slotted along the load-brush (horizontal) axis to indicate a method of achieving satisfactory commutation in the coils being shorted by these brushes. A restriction in the size of the amplidyne is the self-induced voltage in the coils being commutated.

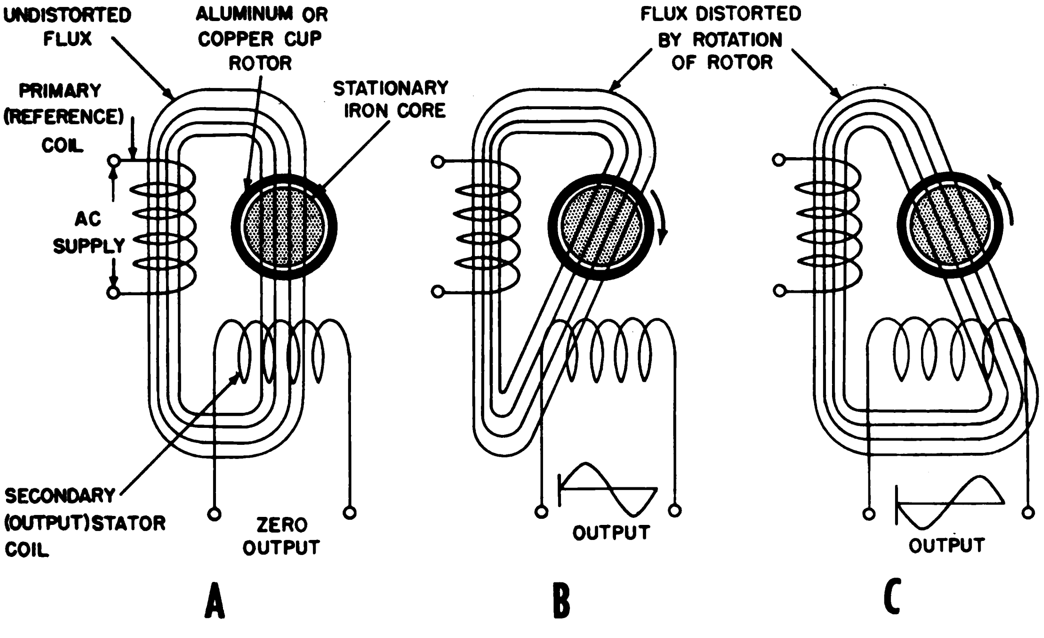
Because any residual magnetism along the axis of the control field would have an appreciable effect on the amplidyne output, it is necessary to demagnetize the core material when the control field winding is deenergized. This demagnetization is accomplished by means of a small a.c. magneto generator (mounted on the amplidyne frame) which supplies a demagnetizing winding, known as a killer winding (fig. 1-8A).

A servosystem using an amplidyne generator is discussed in chapter 4 of this manual.

RATE GENERATORS

Rate generators (usually referred to as tachometer generators) used in servosystems are small a.c. or d.c. generators which develop an output voltage (proportional to the generator r.p.m.) whose phase or polarity is dependent upon the direction of rotation. Direct current rate generators usually have permanent magnetic field excitation, whereas the a.c. units are excited by a constant a.c. supply.

The most common type of a.c. rate generator is the drag-cup type constructed similar to figure 1-5.



A. ROTOR STATIONARY
B. ROTOR TURNING CLOCKWISE
C. ROTOR TURNING COUNTERCLOCKWISE

55.40

Figure 1-9.—A.c. drag-cup rate generator.

The generator has two stator windings 90° apart, and an aluminum or copper cup rotor. The rotor rotates around a stationary soft-iron magnetic core. One stator winding is energized by a reference a.c. source. The other stator winding is the generator output or secondary winding.

The voltage applied to the primary winding creates a magnetic field at right angles to the secondary winding when the rotor is stationary, as shown in figure 1-9A. When the rotor is turned, it distorts the magnetic field so that it is no longer 90 electrical degrees from the secondary winding. Flux linkage is created with the secondary winding and a voltage is induced (fig. 1-9B and C). The amount of magnetic field that will be distorted is determined by the angular velocity of the rotor. Therefore, the magnitude of the voltage induced in the secondary winding is proportional to the rotor's velocity.

The direction of the magnetic field's distortion is determined by the direction of the rotor's motion. If the rotor is turned in one direction, the lines of flux will cut the secondary winding in one direction. If the motion of the rotor is reversed, the lines of flux will cut the secondary winding in the opposite direction. Therefore, the phase of the voltage induced in the secondary winding, measured with respect to the phase of the supply voltage, is determined by the direction of the rotor's motion.

The frequency of the generator output voltage is the same as the frequency of the reference voltage. This is true because the magnetic field produced by the primary winding fluctuates at the supply's frequency. The output voltage is generated by the alternating flux field cutting the secondary winding; therefore, the output voltage must have the same frequency as the supply voltage.

Other types of a.c. rate generators have a squirrel-cage rotor. Otherwise their construction and principles of operation are identical to the drag-cup type.

The d.c. rate generator employs the same principles of magnetic coupling between the reference winding and the output winding as the a.c. generator. The d.c. rate generator, however, has a stationary primary magnetic field. This magnetic field is usually supplied by permanent magnets as stated previously. The amount of voltage induced in the rotor winding is proportional to the magnetic flux lines the winding cuts. The polarity of the output voltage is determined by the direction in which the rotor cuts the lines of magnetic flux.

Rate generators are used in servosystems to supply velocity or damping signals and are sometimes mounted on the same shaft with, and enclosed within, the same housing as the servomotor.

CHAPTER 2

SYNCHROS, PART I

The term "synchro" is an abbreviation of the word "synchronous," and is the name given to a variety of rotary, electromechanical, positioning-sensing devices. Synchros are designed to provide a physical measure of shaft position as the result of an electrical input, or conversely, to provide an electrical output that is a function of its shaft position. Other names used to designate synchros include: Selsyn, Autosyn, Telesyn, and Magslip.

Synchros are used extensively in the weapons, navigation, and control systems of surface ships, submarines, and aircraft. They are used in applications which vary from a simple torque indicating system to a complex computing system.

In the simple synchro torque indicating system, a synchro unit called a transmitter is connected electrically to another similar unit called a receiver. When the rotor of the transmitter unit is moved, the rotor of the receiver moves the same amount.

Synchros are widely used in remote indicating systems. They provide the means for transmitting data to one or more remotely located indicators. These indicators (receivers) provide, among much other information, such data as helm and rudder position, heading, speed, and roll and pitch; engine speeds, shaft r.p.m., and throttle position; aircraft flight stabilization and instrumentation; wind direction and velocity; course, and range of targets and missiles; and train and elevation of searchlights, antennas, guns, and launchers.

In addition to supplying data by positioning dials and pointers, synchros are used in many other applications such as opening and closing electrical contacts, and positioning hydraulic pilot valves. Further, synchros are used in many control applications. For example, a control synchro unit may be used to supply the control signals to servosystems which move such loads as radar antennas, missile launchers, gun turrets, aircraft and ship rudders, and many others.

This chapter presents a general description of the common types of synchro units, explains how they are classified and identified, and discusses the theory of operation of each type.

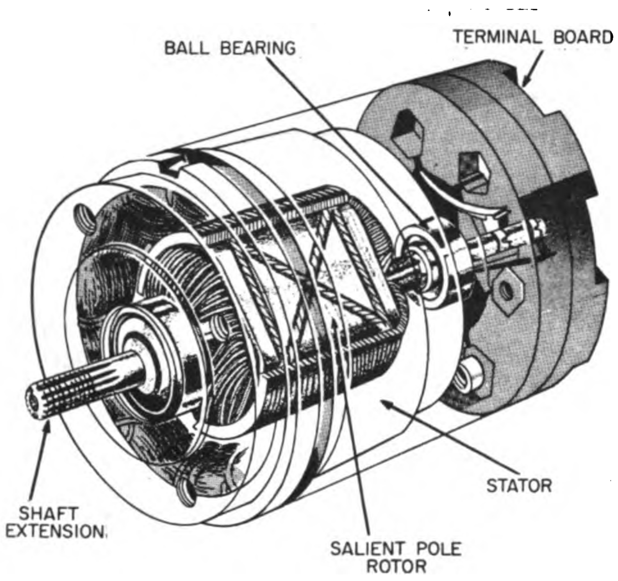
GENERAL CONSTRUCTION

A synchro resembles a small electrical motor in size and appearance but operates like a variable transformer. Each synchro contains a rotor, similar in appearance to an armature, and a stator, which corresponds to the field in a motor as shown in figure 2-1. The synchro is usually composed of a three-winding, Y-connected stator encased in a cylindrical metal shield and a rotor with one winding. The rotor is mounted within the stator and is free to turn within the stator windings. As the one-winding rotor of a synchro is rotated, the amount of coupling in the three stator windings is varied, producing a variable voltage output that represents the amount and direction of displacement of the rotor from the stator.

The rotor (which is usually the primary winding of the synchro unit) is wound on sheet-steel laminations stacked together and securely mounted on a shaft. To enable the excitation voltage to be applied to this winding, two sliprings are mounted on one end of the shaft and insulated from it. An insulated terminal board, mounted on one end of the cylindrical frame, houses the brushes which ride on the sliprings. This terminal board and another insulated block that is mounted on the other end of the synchro frame contain low friction ball-bearings.

CLASSIFICATION

The two general classifications of synchros are torque and control. Torque synchros are used in lightly loaded synchro systems, whereas heavy loaded systems use control synchros.



72.42.1

Figure 2-1.—Phantom view of a synchro.

Torque synchros provide a mechanical output; control synchros provide an electrical output.

Torque synchros are used for light loads such as positioning dials, pointers and similar indicators. A torque transmitter (TX) and a torque reciever (TR) make up a simple torque synchro system. The TX and TR are electrically identical, however, they do differ slightly physically. The TR has an inertia damper (similar to a flywheel) mounted on its shaft to reduce oscillations.

Control Synchros are used in servosystems which position heavy loads such as gun directors, radar antennas, missile launchers, and many others. A control transmitter (CX) and a control transformer (CT) make up a simple synchro control system. The CX is identical to the TX but produces less torque, and has greater accuracy. The CT, as discussed later, supplies an electrical signal output from its rotor corresponding to the shaft position of the CX to which it is connected and is constructed somewhat differently from the other units mentioned previously.

Torque and control synchros are grouped into seven basic functional classes (four torque and three control) as shown in table 2-1.

Synchros may also be classified according to operating frequency. If two synchros of equal power handling ability are built—one designed for 60-Hz excitation and one designed for 400-Hz excitation—the one designed for the higher frequency may be made physically smaller. This miniaturization is limited only by manufacturing and design capabilities.

The physical characteristics and construction of 60-Hz synchros and 400-Hz synchros are similar. Lines of flux produced by the 400-Hz excitation are much more concentrated than those produced by 60-Hz excitation; therefore, the core size of the 400-Hz synchro can be made smaller. If the number of turns in the rotor winding is reduced, the number of turns in the stator winding must be reduced accordingly. Because the transformation ratio is not changed, the power output of the smaller 400-Hz synchro can be the same as the power output of a 60-Hz excited synchro.

Space saving is important. Smaller synchros allow smaller indicating units, thereby saving space for other equipment. Aircraft space requirements brought about the first attempt to reduce the physical size of synchros. Now, 400-Hz is the predominant frequency specification for airborne equipment, and it is also specified for certain shipboard equipments.

STANDARD MARKINGS AND SYMBOLS

Synchros used in the Navy can be grouped into two broad categories: military standard synchros and prestandard Navy synchros. Military standard synchros conform to specifications which are uniform throughout the Armed Services. New equipments use synchros of this type. Prestandard synchros were made to meet Navy, rather than service-wide, specifications. Each category has a designation code for identification.

MILITARY STANDARD DESIGNATION CODE

This designation code identifies standard synchros by their physical size, functional purpose, and supply voltage characteristics. We will use two standard synchro designations: 18TR6 and 16CTB4a, as examples to explain the code. The first two digits indicate the diameter of the synchro in tenths of an inch, or to the next higher tenth. Thus an actual dimension of 1.75 inches becomes 18. The first letter indicates the general function of the synchro and of the synchro system: C for control; T for torque.

12.328

Table 2-1.—Synchro information

Functional Classification	Military Abbreviations	Input	Output
Torque Transmitter	TX	Rotor positioned mechanically or manually by information to be transmitted	Electrical output from stator identifying rotor position supplied to torque receiver, torque differential transmitter, or torque differential receiver
Control Transmitter	CX	Same as TX	Electrical output same as TX but supplied only to control transformer or control differential transmitter
Torque Differential Transmitter	TDX	TX output applied to stator; rotor positioned according to amount data from TX must be modified	Electric output from rotor (representing angle equal to algebraic sum or difference of rotor position angle and angular data from TX) supplied to torque receivers, another TDX, or a torque differential receiver
Control Differential Transmitter	CDX	Same as TDX but data usually supplied by CX	Same as TDX but supplied only to control transformer or another CDX
Torque Receiver	TR	Electrical angular position data from TX or TDX supplied to stator	Rotor assumes position determined by electrical input supplied
Torque Differential Receiver	TDR	Electrical data supplied from two TDX's, two TX's or one TX and one TDX (one connected to rotor, one to stator)	Rotor assumes position equal to algebraic sum or difference of two angular inputs
Control Transformer	CT	Electrical data from CX or CDX applied to stator; rotor positioned mechanically or manually	Electrical output from rotor (proportional to sine of the difference between rotor angular position and electrical input angle)

The next letter indicates the specific function of the synchro, as follows:

LETTER	DEFINITION
D	Differential
R	Receiver
T	Transformer
X	Transmitter

The letter B following the preceding letters indicates that the synchro has a rotatable stator. The number after the letters stands for the operating frequency (6 for 60-Hz and 4 for 400-Hz). The lower case letter is a modification designation. Successive modifications are in alphabetical order.

Thus, an 18TR6 synchro is a 60-Hz torque receiver with a diameter of between 1.71 and 1.80 inches. The 16CTB4a is the first modification of a 400-Hz control transformer with a rotatable stator and a diameter of between 1.51 and 1.60 inches.

Type designations for all standard synchros are assigned by this code. Synchros for use in circuits supplied by 26 volts are classified in the same way, except that the symbol 26V is prefixed to the designator. Otherwise, a 115-V source is assumed for the synchro system. Note that in table 2-1 only the functional designator is given. This is often the practice used in schematic diagrams. The complete identification is normally given in the physical description section or parts list of the manual or print concerned.

NAVY PRESTANDARD DESIGNATION CODE

This code identifies prestandard synchros as to their size and function by a number and letter combination. Unlike the standard code, the number does not directly indicate the diameter of the synchro. The number indicates relative size of the synchro. The size increases with the number. The letters indicate the function, mounting, or special characteristics as follows:

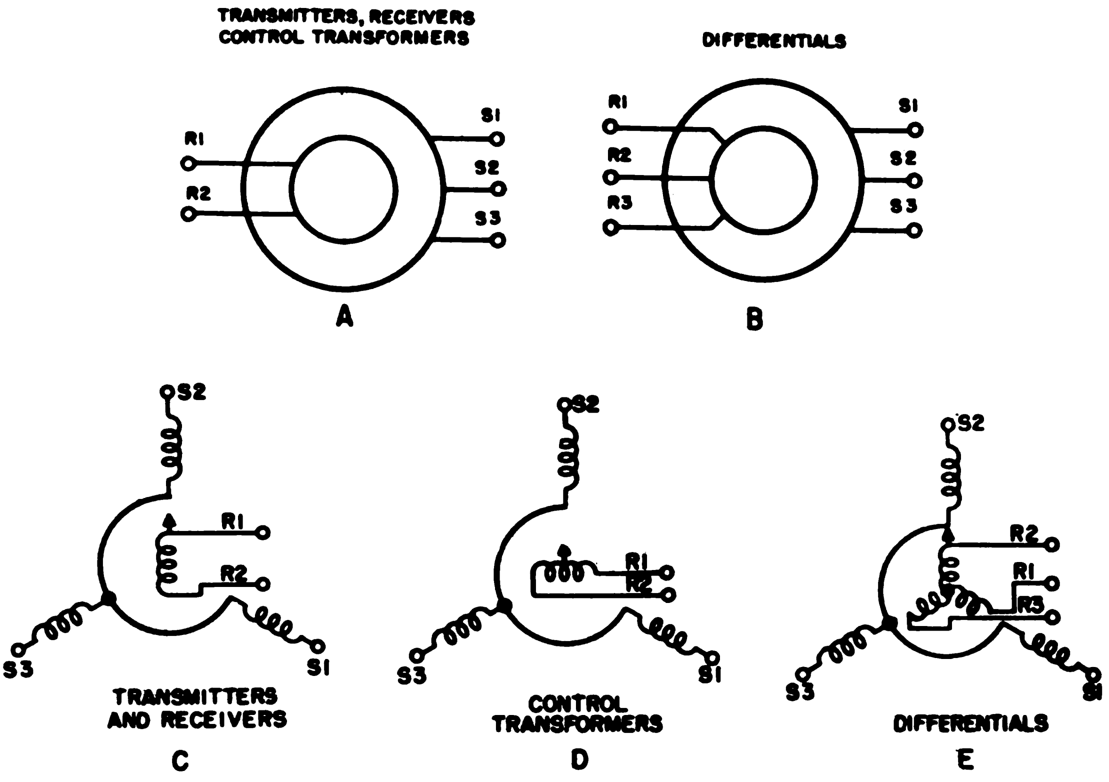
Letter	Definition
G	Transmitter
F	Flange mounted receiver, this letter is normally omitted if letters other than H or S occur in type designation.
D	Differential Receiver
DG	Differential Transmitter
CT	Control Transformer
H	High Speed Unit
B	Bearing Mounted Unit
N	Nozzle Mounted Unit
S	Special Unit

In some texts synchro transmitters, TX, are called generators, and receivers, TR, ar called motors.

SCHEMATIC SYMBOLS

Schematic symbols for synchros are draw by their manufacturers in many different ways, Only five symbols as shown in figure 2-2 however, meet the standard military specification for schematic diagrams of synchros and synchr connections. Appearing close to the symbol ma be a military abbreviation of one of the seve functional classifications of synchros.

The letters R and S are used to identify th rotor and stator connections. The symbols show in (A) and (B) of figure 2-2 are used when it i



1.119:.120(72)
Figure 2-2.—Schematic symbols for synchros.

necessary to show only the external connections to a synchro, while those shown in (C), (D), and (E) are used when it is important to see the positional relationship between the rotor and stator. The small arrow in the rotor symbol indicates the angular displacement of the rotor; in figure 2-2 the displacement is zero degrees.

SYNCHRO PRINCIPLES

The conventional synchro unit is essentially a transformer with a rotatable primary winding and three secondary windings spaced 120° apart as shown in figure 2-3.

When an a.c. voltage is applied to the rotor (primary) winding of a synchro, a magnetic field is set up around the soft iron, laminated core of the rotor. This magnetic field induces voltages into the three Y-connected stator (secondary) windings.

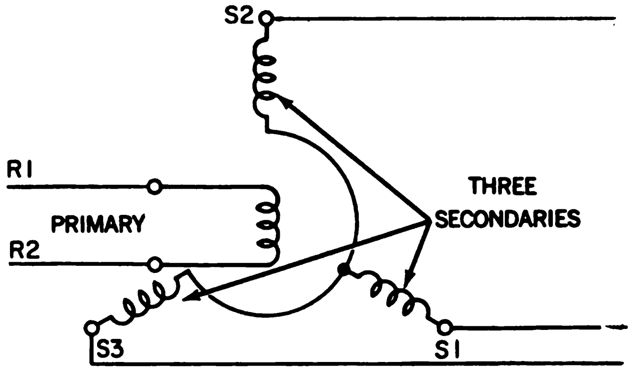
STATOR VOLTAGES VS ROTOR POSITION

The angular displacement of the rotor from the reference position varies the induced voltage in each stator winding by an amount equal to the cosine of the angle of displacement. In other words, as the position of the rotor is changed in relation to the stator, the voltage induced in each stator winding varies as a function of the angular displacement of the rotor from the stator.

If the position of the rotor is parallel to one of the stator windings, maximum voltage will be induced into that winding. The voltages induced into the other two stator windings are then equal because their angles of displacement are equal.

The maximum voltage induced in any one stator winding of a 115-volt synchro is 52 volts. This occurs only when the stator winding is parallel to the rotor. The voltage induced in one stator winding, however, cannot be measured because the common point of the three Y-connected windings does not appear as a terminal on the outside of the synchro case. Since the end terminals of the three windings are the only stator terminals that are led outside the synchro case, only the voltage induced between any two stator terminals can be measured.

Figure 2-4 shows the voltage induced in each stator coil and the voltage between stator terminals when the rotor is parallel to the S2 coil. As the rotor is parallel to the S2 coil, a maximum of 52 volts is induced in the S2 coil. This 52 volts is in phase with (or has the same instantaneous polarity as) the rotor voltage.



175.6

Figure 2-3.—Transformer with one primary winding and three secondary windings.

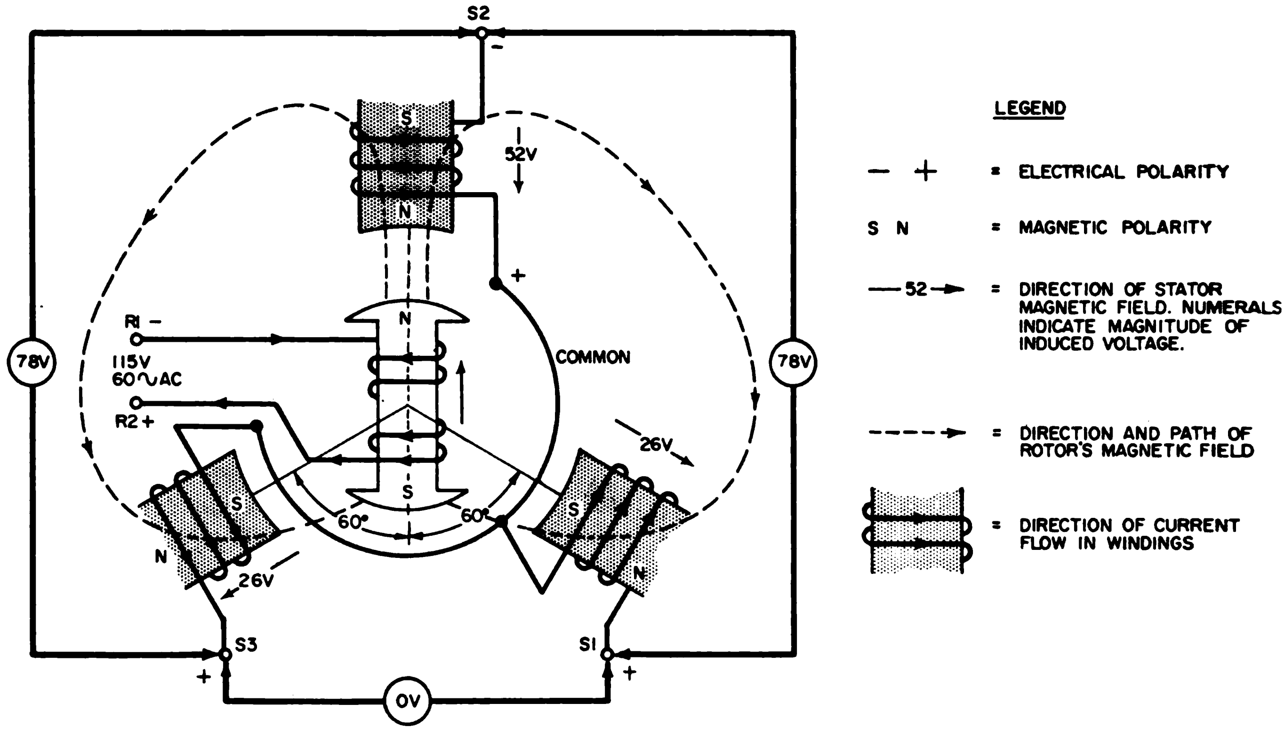
Stator coils S1 and S3 are at a 60° angle to the rotor and therefore have less voltage induced in them. The cosine of 60° is .5, thus, coils S1 and S3 have a voltage of .5 x 52 or 26 volts.

The voltages induced in the S1 and S3 coils are 180° out of phase with the rotor voltage. For example, the voltage from S1 or S3 to the common connection will be positive at the same instant that R1 is negative in respect to R2. The S1 and S3 voltages are equal and have the same instantaneous polarities, therefore, there is no difference of potential between terminals S1 and S3.

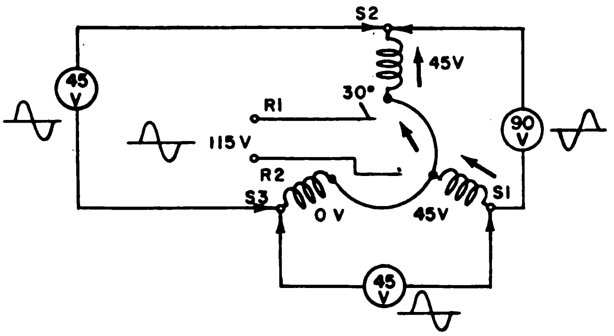
The S2 coil voltage is in series with and aiding the S1 coil voltage, thus, the voltage from terminal S1 to S2 is 52 + 26 or 78 volts. Similarly, the S2 to S3 terminal voltage is the sum of the voltages induced in the S2 and S3 coils. It is important to remember that synchros are excited by a single phase supply, therefore, all voltages rise and fall in unison and are either in phase or 180° out of phase.

When the rotor of a conventional synchro transmitter or receiver is aligned parallel with the S2 coil as shown in figure 2-4, the synchro is said to be on electrical zero. The electrical zero position for the various types of synchro units is discussed in the next chapter.

Figure 2-5 shows the synchro rotor positioned 30° counterclockwise (CCW) from the electrical zero position. In this position, the rotor is no longer parallel to the S2 coil, so


S2
52V
+
R1 −
115V
60∿AC
R2 +
N
S
COMMON
78V
78V
26V
26V
60°
60°
S
N
S
N
S3
S1
+
+
0V
LEGEND
− + = ELECTRICAL POLARITY
S N = MAGNETIC POLARITY
—52→ = DIRECTION OF STATOR MAGNETIC FIELD. NUMERALS INDICATE MAGNITUDE OF INDUCED VOLTAGE.
----→ = DIRECTION AND PATH OF ROTOR'S MAGNETIC FIELD
= DIRECTION OF CURRENT FLOW IN WINDINGS

12.166
Figure 2-4.—Synchro voltages, rotor at 0°.



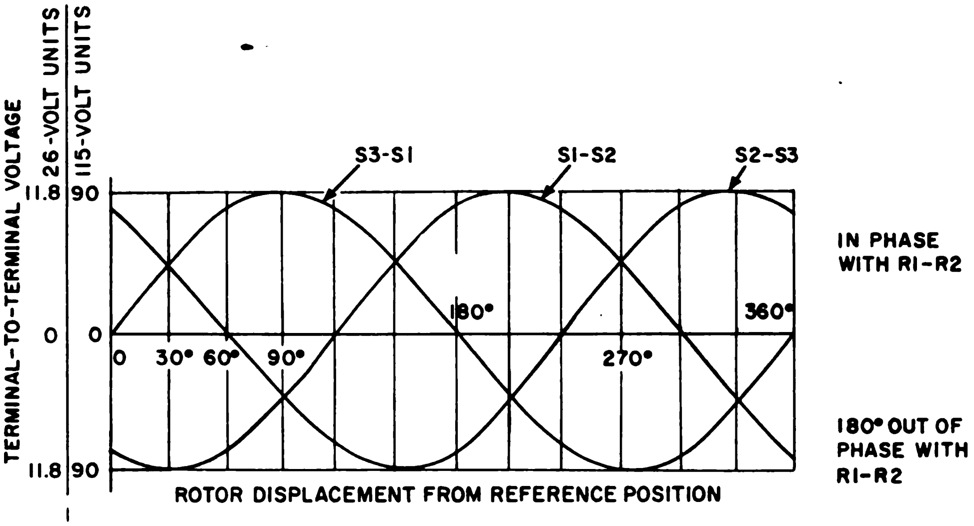
83.71.1
Figure 2-5.—Synchro voltages, rotor at 30°.

it induces only 45 volts in the S2 coil (.866 x 52 = 45 volts). Likewise, the rotor is displaced 30° from the S1 coil and induces 45 volts in this coil. The rotor being at right angles (displaced 90°) to the S3 coil induces no voltage in the S3 coil. A voltmeter connected to the stator terminals would show the following: S1 to S2, 90 volts; S2 to S3, 45 volts; and S1 to S3, 45 volts. These stator voltages correspond to the 30° CCW position of the rotor from the electrical zero position. A different combination of stator voltages exists for each angular position of the rotor. Thus, the stator voltages represent the rotor position.

The 90 volt terminal-to-terminal stator voltage at the 30° CCW rotor position (fig. 2-5) is the maximum terminal-to-terminal voltage for 115 volt synchros. The maximum voltage induced in any one coil, however, is 52 volts as discussed earlier. Figure 2-6 shows the terminal-to-terminal stator voltages for 115 and 26 volt synchros for all rotor positions from 0° CCW to 360°.

SIMPLE SYNCHRO SYSTEM

A simple synchro transmission system consists of a transmitter connected to a receiver, as shown in figure 2-7. The R1 transmitter and R1 reciever leads are connected to one side of the a.c. supply line and the R2 transmitter and R2 receiver leads are connected to the other side of the supply line. The stators of both



83.71.2
Figure 2-6.—Terminal-to-terminal voltages.

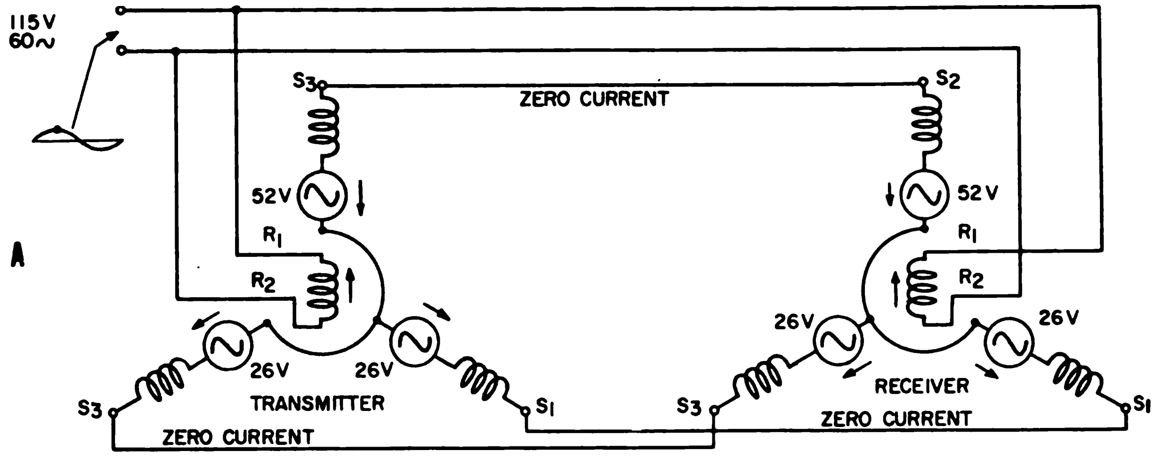
the transmitter and the receiver are connected S1 to S1, S2 to S2, and S3 to S3 so that the voltage in each of the transmitter stator coils opposes the voltage in the corresponding coils of the receiver stator. The voltage directions are indicated by arrows for the instant of time shown by the dot on the sine wave of the rotor supply voltage.

The field of the transmitter is aligned with the axis of S2 (fig. 2-7A) because the transmitter rotor axis is aligned with S2. Assume for the moment that the receiver rotor is not connected to the single-phase supply. Under this condition the voltage induced in the transmitter stator windings will be impressed on the receiver stator windings through the three leads connecting the S1, S2, and S3 terminals. Exciting currents that are proportional to the transmitter stator voltages will flow in the receiver stator windings, and the magnetomotive forces produced by these currents will establish a 2-pole field that orients itself in the receiver stator in exactly the same manner that the transmitter field is oriented in its own stator. Thus, if the transmitter field is turned by turning the transmitter rotor, the receiver field will also turn in exact synchronism with the transmitter rotor.

A soft-iron bar placed in a magnetic field will always tend to aline itself so that its longest axis is parallel to the axis of the field. Thus, the salient pole receiver rotor will also aline itself with the receiver field even though the receiver rotor winding is open-circuited. Operation with an open-circuited rotor is not desirable, however, because for a given position of the transmitter rotor and field there are two positions, 180° apart, in which the salient pole receiver rotor may come into alinement with the receiver field. This difficulty is eliminated by energizing the receiver rotor with alternating current of the same frequency and phase as that supplied to the transmitter rotor. Now the receiver rotor electromagnet comes into alignment with the receiver field in such a position as to always aid the magnetomotive forces of the three windings of the receiver stator.

When both rotors are displaced from zero by the same angle, they are properly aligned with their respective stator fields. Under this condition they are in correspondence and the induced voltages in each of the three pairs of corresponding stator coils are equal and in opposition. Hence, there is no resultant voltage between corresponding stator terminals and no current flows in the stator coils.

The angle through which a transmitter rotor is mechanically rotated is called a SIGNAL. For example, the angle that the transmitter rotor is displaced (fig. 2-7B) is 60°. As soon as the transmitter rotor is turned, the transmitter S2 coil voltage decreases, the S1 coil voltage reverses direction, and the S3 coil voltage increases. Current immediately flows



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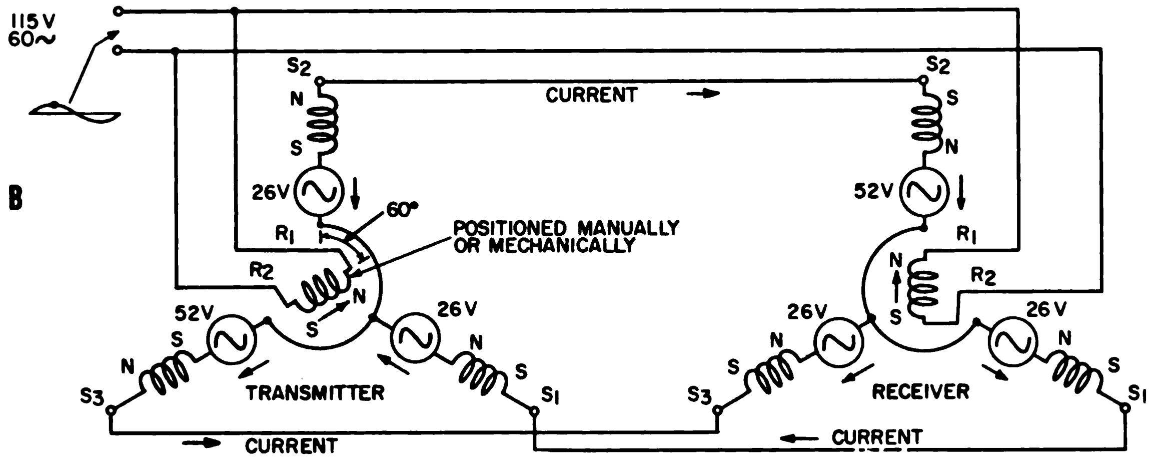

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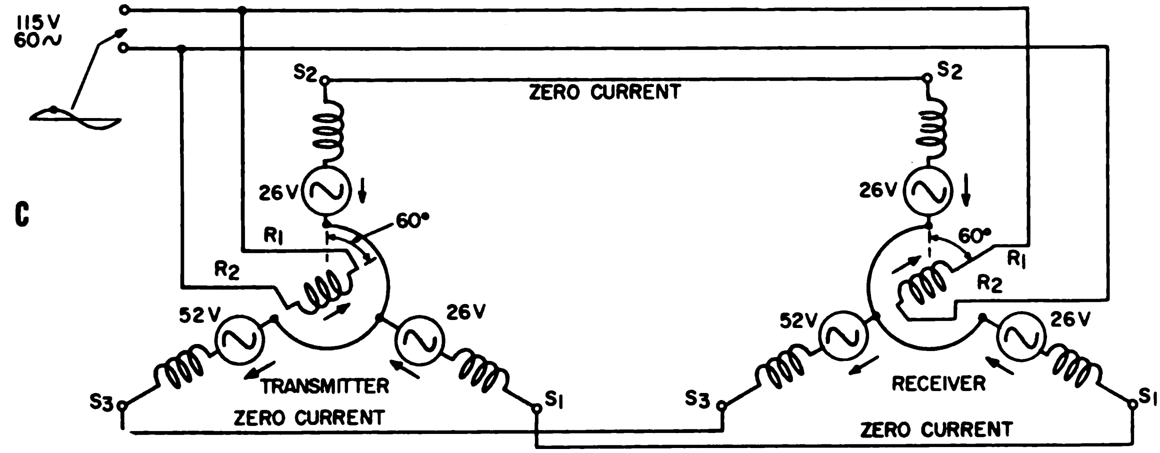


System again in correspondence.

53.11:.12(72)
Figure 2-7.—Simple TX-TR synchro system.

between the transmitter stator and the receiver stator in the direction of the stronger voltages. The unbalanced voltages are absorbed in the line drop and in the internal impedances of the windings.

When the transmitter (fig. 2-7A) is turned clockwise 60 degrees (fig. 2-7B), a torque is developed in the receiver rotor causing it to attempt to follow through the same angle. When the receiver and the transmitter are again in alinement, the torque is reduced to zero, as shown in 2-7C.

As a receiver approaches correspondence, the stator voltages of the transmitter and receiver approach equality. This action decreases the stator currents and produces a decreasing torque on the receiver that reduces as the position of correspondence is reached. At correspondence, the torque on the receiver rotor is only the amount that is caused by the tendency of the salient-pole rotor to aline itself in the receiver field. Hence, a receiver can position only a very light load.

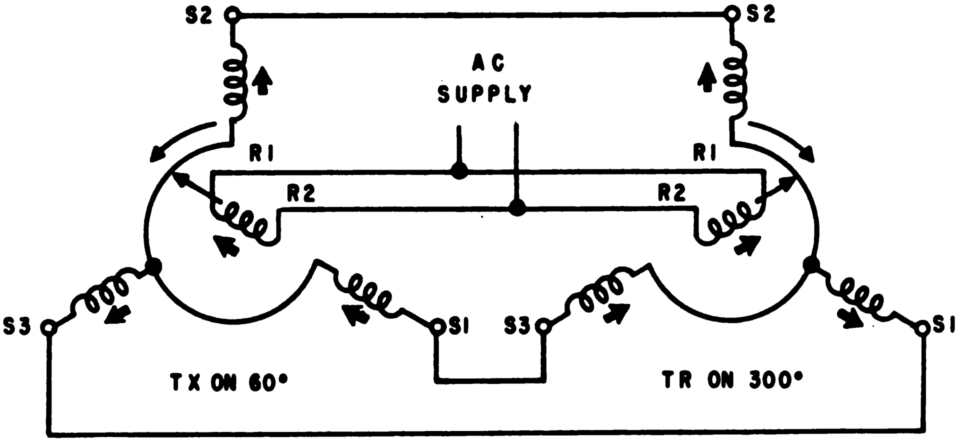
Synchro receivers are often connected through a train of mechanical gears to the device which they operate, and whether or not force is applied to the device in the same direction as that in which the receiver rotor turns depends on whether the number of gears in the train is odd or even.

The important thing, of course, is to move the dial or other device in the proper direction, and even when there are no gears involved, this may be opposite to the direction in which the receiver rotor of a normally connected system would turn.

Either of these two factors, and sometimes a combination of both, may make it necessary to have the transmitter turn the receiver rotor in a direction opposite to that of its own rotor. This is accomplished by reversing the S1 and S3 connections of the transmitter-receiver system, so that S1 of the transmitter is connected to S3 of the receiver and vice versa. This is shown in figure 2-8.

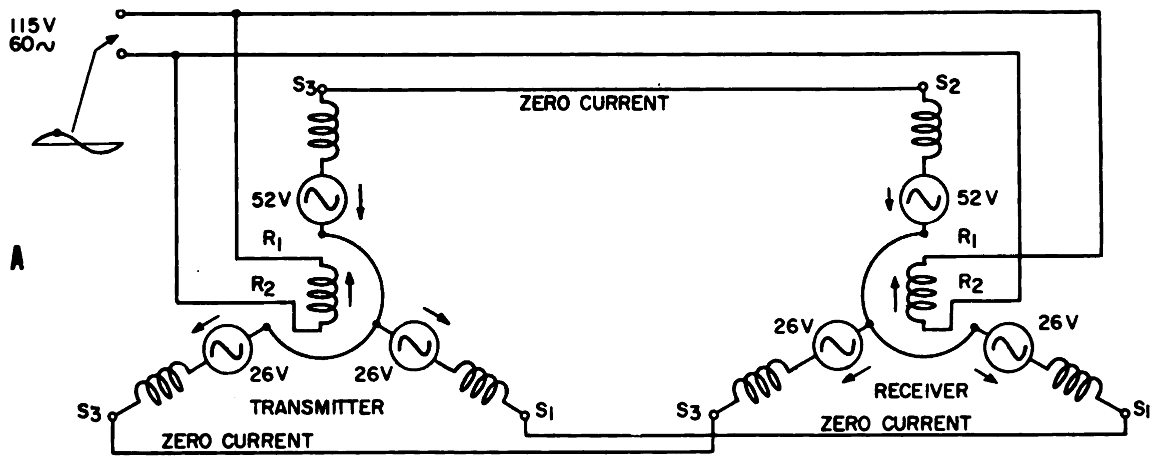
With both rotors at zero degrees, conditions within the system remain the same as during normal stator connections, since the rotor coupling to S1 and S3 is equal. But suppose that the transmitter rotor is turned counterclockwise to 60 degrees, as shown in figure 2-8. In the transmitter, maximum rotor coupling induces maximum voltage across S1, which causes maximum current to flow through S3 in the receiver. The magnetic forces produced turn the receiver rotor clockwise into line with S3, the rotor's 300-degree position, at which point the rotor again induces voltages in its stator coils which equal those of the transmitter coils to which they are connected. Notice that only the direction of rotation changes, not the amount; the 300-degree position is the same as the minus 60-degree position.

It is important to emphasize that the S1 and S3 connections are the only ones ever interchanged in a standard synchro system. Since S2 represents electrical zero, changing the S2 lead would introduce 120-degree errors in indication, and also reverse the direction of rotation.



53.14

Figure 2-8.—Effect of reversing S1 and S3 connections between the transmitter and receiver.



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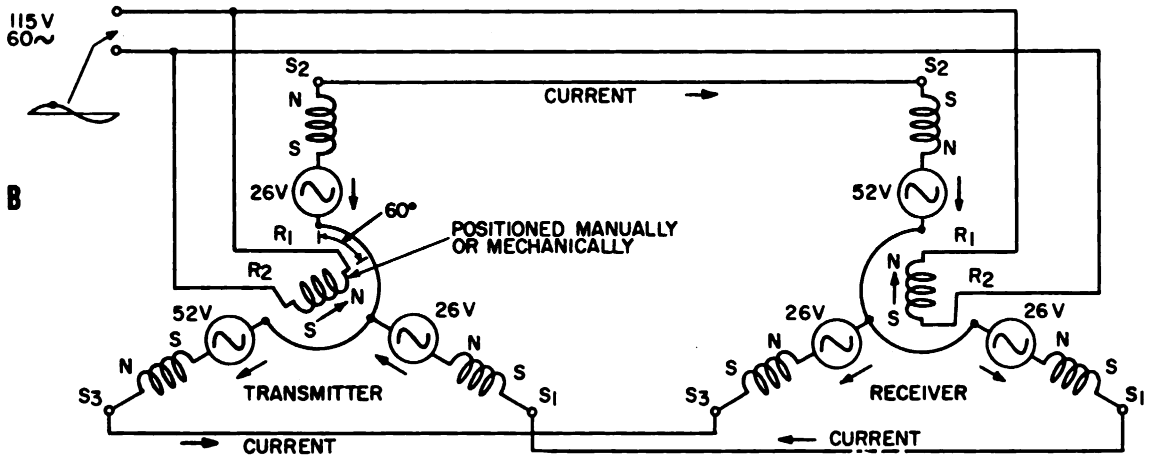

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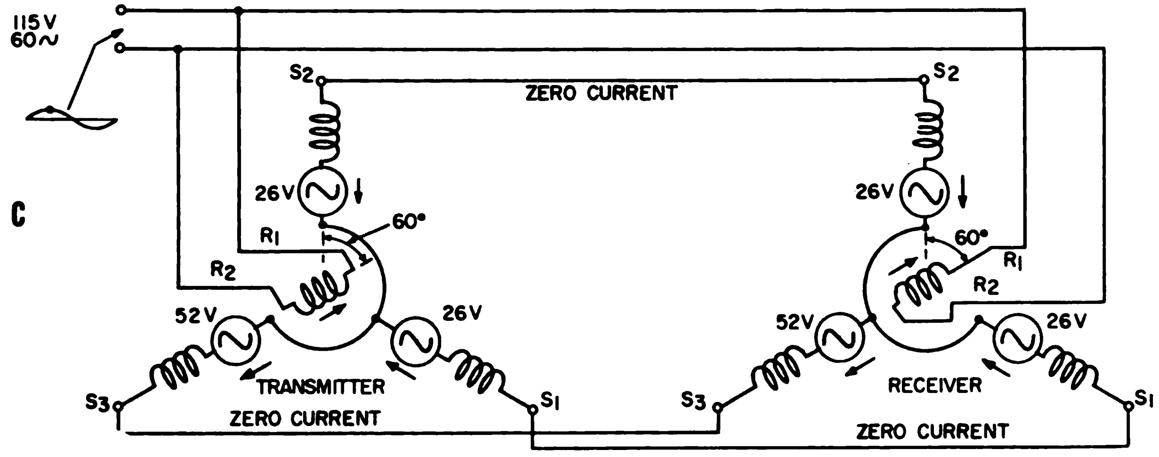

System again in correspondence.

53.11:.12(72)

Figure 2-7.—Simple TX-TR synchro system.

between the transmitter stator and the receiver stator in the direction of the stronger voltages. The unbalanced voltages are absorbed in the line drop and in the internal impedances of the windings.

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As a receiver approaches correspondence, the stator voltages of the transmitter and receiver approach equality. This action decreases the stator currents and produces a decreasing torque on the receiver that reduces as the position of correspondence is reached. At correspondence, the torque on the receiver rotor is only the amount that is caused by the tendency of the salient-pole rotor to aline itself in the receiver field. Hence, a receiver can position only a very light load.

Synchro receivers are often connected through a train of mechanical gears to the device which they operate, and whether or not force is applied to the device in the same direction as that in which the receiver rotor turns depends on whether the number of gears in the train is odd or even.

The important thing, of course, is to move the dial or other device in the proper direction, and even when there are no gears involved, this may be opposite to the direction in which the receiver rotor of a normally connected system would turn.

Either of these two factors, and sometimes a combination of both, may make it necessary to have the transmitter turn the receiver rotor in a direction opposite to that of its own rotor. This is accomplished by reversing the S1 and S3 connections of the transmitter-receiver system, so that S1 of the transmitter is connected to S3 of the receiver and vice versa. This is shown in figure 2-8.

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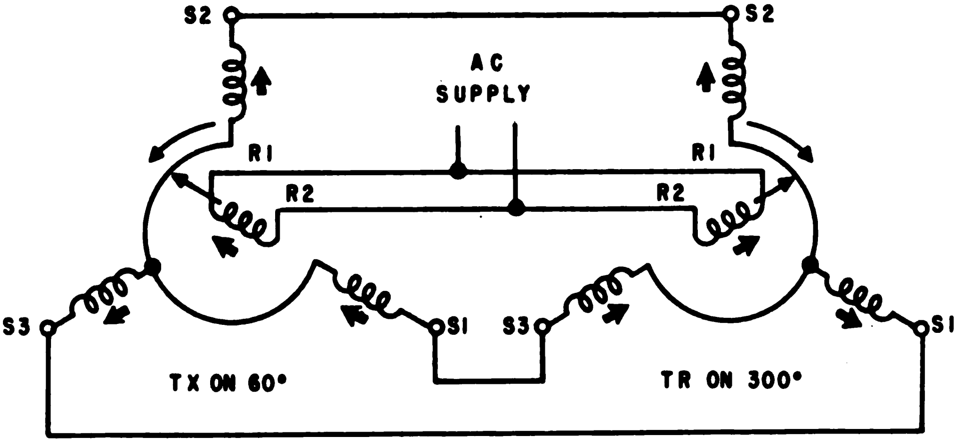
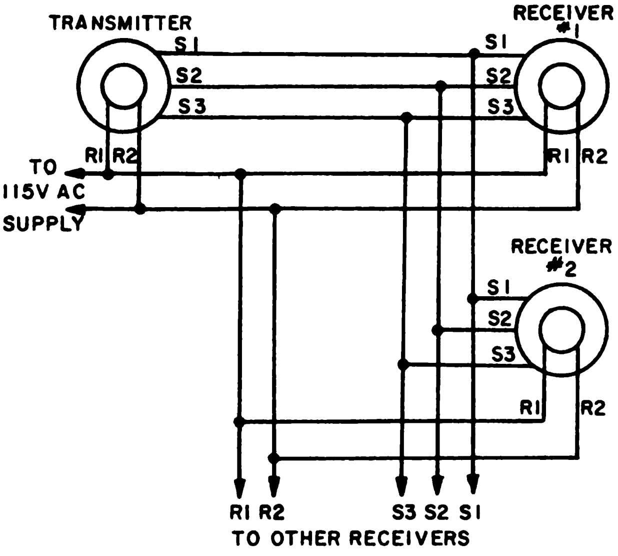


53.14

Figure 2-8.—Effect of reversing S1 and S3 connections between the transmitter and receiver.

Many installations connect one transmitter to several receivers in parallel. This procedure requires a transmitter large enough to carry the total load current of all the receivers. All the R1 rotor leads are connected to one side of the a.c. power supply, and all the R2 rotor leads are connected to the other side of the supply. The receiver stator leads are connected lead for lead to the transmitter stator leads as shown in figure 2-9.



175.7

Figure 2-9.—Synchros in parallel.

DIFFERENTIAL SYNCHROS

The demands on a synchro system are not always as simple as the positioning of an indicating device in response to the information received from a single source (transmitter). For example, an error detector used in checking fire-control equipment employs a synchro system to determine the error in a gun turret's position with respect to the training order supplied by a dummy director. To do this, the synchro system must accept two signals, one containing the training order and the other corresponding to the turret's actual position. The system must then compare the two and position an indicator to show the difference between them, which is the error.

Obviously, the simple synchro transmitter-receiver system considered up to now could not handle a job of this sort. A different type of synchro is needed, one which can accept two position-data signals simultaneously, add or subtract the data, and furnish an output proportional to the sum or difference of the two. Differential synchros can perform these functions.

There are two types of differential units: differential transmitters and differential receivers. A differential transmitter accepts one electrical input and one mechanical input and produces one electrical output. A differential receiver accepts two electrical inputs and produces one mechanical output.

Differential transmitters may be used in either torque synchro systems or control synchro systems. Differential receivers are an integral part of torque synchro systems; however, they are not normally used in control synchro systems.

A torque differential transmitter (TDX) provides an electrical output from its rotor to the stator of a torque receiver (TR) or a torque differential receiver (TDR). This electrical output of the TDX may be either the sum or difference of two inputs: an electrical input from a torque transmitter (TX) and a mechanical input such as a handcrank. Whether the output represents the sum or the difference of the two inputs depends upon how the three units, the TX, the TDX, and the TR, are connected.

A control differential transmitter (CDX) provides the same type of output as the TDX. The CDX however, is designed for greater accuracy and produces less torque than the TDX, and usually supplies an input to a control transformer or another CDX in a control system.

A TDR provides a mechanical output from its shaft. This mechanical output may be either the sum or difference of electrical inputs to both the rotor and stator from two different torque transmitters or torque differential transmitters. Again, the addition or subtraction function depends upon how the units are connected.

Most synchros use the rotor as the primary winding, but in the synchro differential transmitter, the stator is usually the primary. Excitation comes from the stator of a torque or control differential transmitter. Induced voltages in the rotor are passed to another differential unit or to a synchro receiver.

Although the differential receiver acts as a transformer, neither the stator nor the rotor could be classed as the primary winding. Both sets of windings are a.c. excited with the rotor having a mechanical output to a pointer or dial indicator. The stator is normally connected to the closest or higher current rating transmitter.

CONSTRUCTION

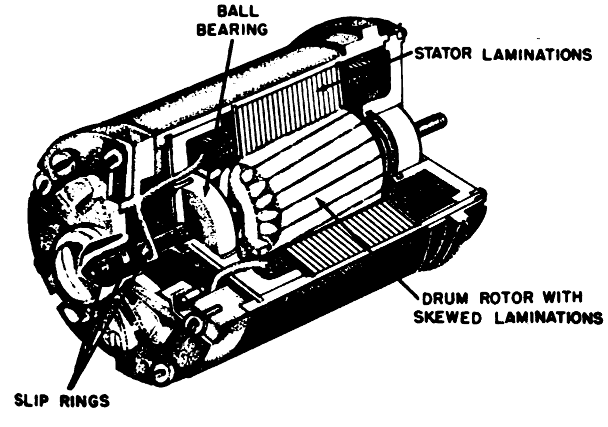
The rotor construction of a TDX is different from that of a TX. Salient pole, single-winding rotors are used in most torque synchro transmitters and receivers; synchro differential units use the drum or slotted rotor, as shown in figure 2-10, for more precise control of the magnetic field. Three sliprings are needed in a synchro differential because of the Y-connected rotor windings.

The stacked laminations of the drum-wound rotor of the differential synchro are slanted (skewed) to prevent "slot lock." "Slot lock" is a cogging effect produced by the interaction between the magnetic fields of the rotor and the stator when the slots between the stacked laminations are parallel to the rotor shaft centerline. Skewing the slots of either the rotor or stator of a synchro unit eliminates the possibility of "slot lock," thus making the unit more sensitive.

The TDR is constructed the same as the TDX with one exception. As with other receivers, the TDR needs damping action. This is provided either by the heavy flywheel friction device mounted on the rotor or by a quadrature voltage winding on the rotor or stator.

THEORY OF OPERATION

As stated previously, the method of interconnecting the units in a differential synchro system determines whether the differential output is the sum or difference of the two inputs.



175.8
Figure 2-10.—Cutaway view of differential synchro.

The term "standard synchro connections" (discussed in chapter 3), is defined as the connection arrangement which allows an increasing value of output from one unit to produce an increasing value of input to a second unit. This may be stated in other terms by saying that counterclockwise rotor rotation of one unit will produce counterclockwise rotor rotation of a second unit.

Nonstandard synchro connections deviate from the standard arrangement only in that stator leads S1 and S3 are reversed on one of two units. Stator lead S2 is connected to another S2 stator terminal for either the standard or nonstandard arrangement.

The fact that both the TX rotor and the TDX rotor are held in position is important and should be kept in mind. That is, the rotors are physically held in position and movement of one rotor does not produce movement of the other. The second rotor would move so that it could aline itself with the new field, but it cannot because it is physically held in its original position. The TDR rotor, however, is always free to rotate.

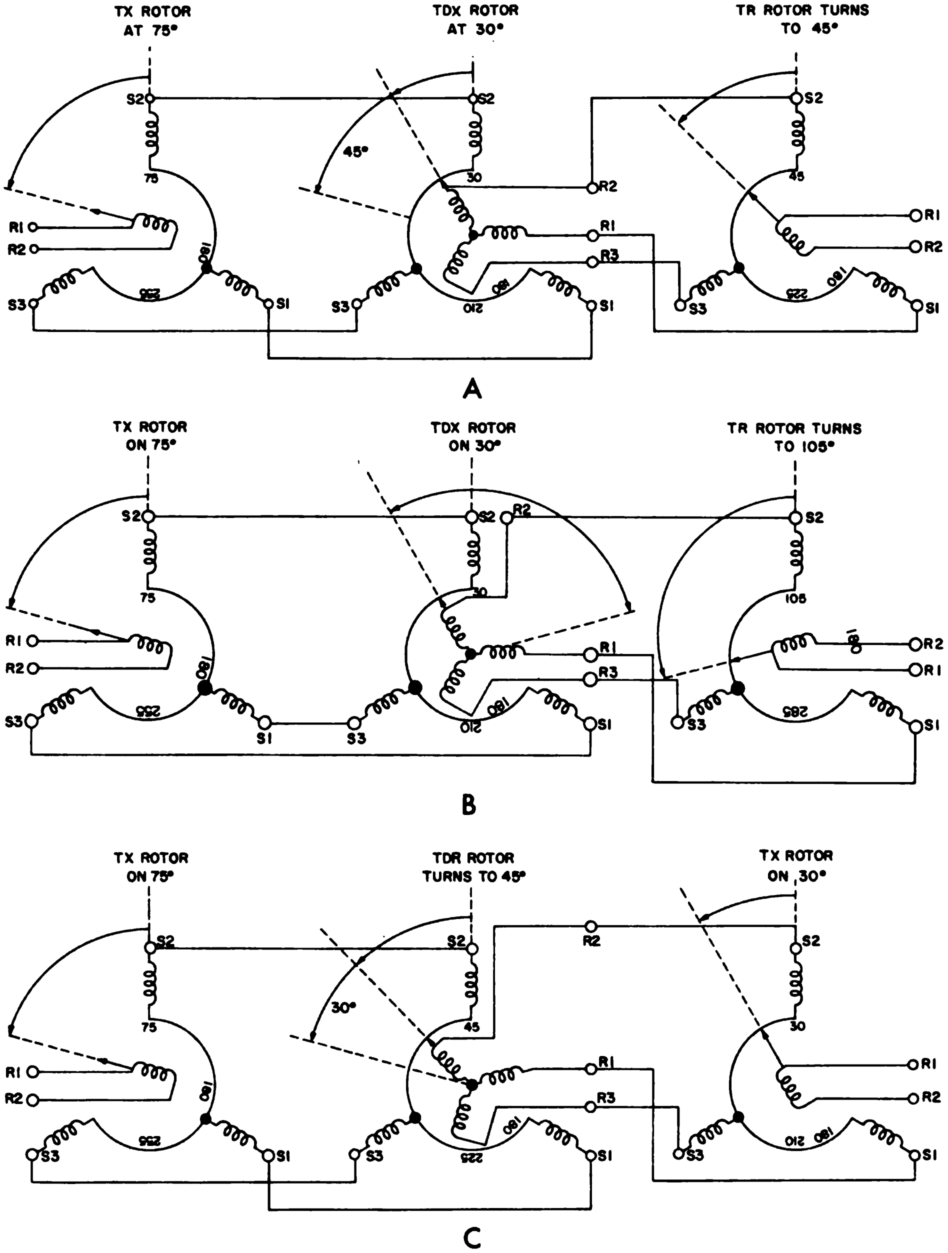
Subtraction With TDX

Figure 2-11A illustrates an example of a TDR producing the difference between its two inputs. Note that the synchro connections are standard and that rotor position is referenced to the 0° position when the rotor is aligned with stator winding S2.

The illustrated problem of subtraction began with all rotors at their 0° positions. The TX rotor was rotated 75° counterclockwise; thus, the first input was 75° and positive. The TDX rotor would have followed the movement of the TX rotor, but it was physically held in place. This caused a 75° unbalance between the fields of the TDX rotor and stator.

The second input to the system was inserted by manually driving the TDX rotor 30° counterclockwise; thus, the second input was 30° and positive.

By rotating the TDX rotor in the positive direction, the amount of unbalance between the TDX rotor and stator was reduced. Since the amount of unbalance is the amount of input to the TR, the TR rotor moved to indicate the difference between the two inputs. The TX input (+75°) minus the TDX input (+30°) = the TR output (+45°).



175.9
Figure 2-11.—Differential synchros.

Addition With TDX

A TDX produces the sum of two outputs when the synchro connections are nonstandard. In figure 2-11B, the connections for addition, note that TX stator lead S3 is connected to TDX stator lead S1, and that TDX rotor lead R3 is connected to TR stator lead S1. These connections are termed "reverse" or "nonstandard."

It is important to realize that, because of the reversed synchro connections, reverse rotation results. Counterclockwise rotation of the

X rotor causes a positive unbalance between he fields of the TDX rotor and stator. If the DX rotor were free to move, it would indicate he positive input but would rotate in a clockwise irection. Since the TDX rotor cannot move, t transmits its unbalance to the stator of the R, causing the TR rotor to indicate a positive nput by rotating counterclockwise.

The illustrated problem of addition began with ll rotors at their 0° positions. The TX rotor vas rotated 75° counterclockwise; thus, the first nput was 75° and positive. The TDX rotor would ave followed the movement of the TX rotor, ut it was physically held in place. This caused 75° unbalance between the field of the TDX otor and stator.

The second input to the system was inserted by manually driving the TDX rotor 30° counterclockwise; thus, the second input was 30° and negative. The negative sign comes from the reverse rotation. If counterclockwise rotation of the TX rotor is considered positive, clockwise rotation of the TDX must be considered positive due to the fact that the two units are connected for reverse rotation.

The amount of unbalance between the field of the TDX rotor and stator was 0° at the beginning of the problem, was increased to 75° by the first input, and was increased another 30° by the second input. Thus, the total unbalance became 75° + 30° or 105°.

Subtraction With TDR

Torque differential receivers are driven by the outputs of two torque transmitters; thus, both TDR inputs are electrical. The TDR output is a torque generated by movement of the TDR rotor shaft.

Figure 2-11C illustrates a torque synchro system containing two TX units and one TDR unit. In this type of system, the two TX rotors are physically held in place, and the TDR rotor is allowed to move freely. In the illustrated problem, the first input was of 75° in the counterclockwise direction; thus, the first input was a positive 75°. The second input was 30° in the counterclockwise direction; therefore, it was a positive 30°. The unbalance between the two inputs was the amount of TDR rotor movement.

Beginning with all rotors positioned at their 0° reference points, an input of +75° was inserted into the system by manually positioning the rotor of the TX which is illustrated on the left (fig. 2-11C). The TDR rotor responding by rotating 75° in the counterclockwise direction. Keep in mind that since the second TX, illustrated on the right, had not yet supplied an input, its rotor was still at its initial 0° reference position.

To summarize the action thus far, the first TX rotor moved to 75°, the second TX rotor stayed at 0°, and the TDR rotor moved to 75°.

The second input of +30° was then inserted into the system by manually positioning the rotor of the second TX 30° in the counterclockwise direction. Thus, the relative difference between the two TX rotors was 75° - 30° = 45°. The TDR rotor, in order to indicate the difference, rotated 30° in the clockwise direction to indicate 45°.

Standard synchro connections between the two TXs and the TDR allow the difference between the two TX inputs to appear as a torque output on the rotor shaft of the TDR. It follows that, if the synchro connections at the two TXs are made nonstandard, the TDR output will be the sum instead of the difference.

CONTROL TRANSFORMER

The control transformer (CT) is a control synchro unit designed to supply from its rotor terminals, an a.c. signal voltage whose magnitude and phase is dependent upon the rotor angular position from electrical zero, and on the voltages applied to the stator windings. The construction and physical appearance of the CT are similar to the CX except that the rotor of the CT is drum-wound rather than salient pole. The CT output is taken from the rotor via slip rings and brushes.

Since the rotor winding of the CT is never connected to the a.c. supply, it induces no voltage in the stator coils. As a result, the CT stator currents are determined only by the voltages applied to them. The rotor itself is wound so that its position has very little reflected effect on the stator currents. Also, there is never any appreciable current flowing in the rotor, because its output voltage is always applied to a high-impedance load, 10,000 ohms or more. Therefore, the rotor does not turn to any particular position when voltages are applied to the stator.

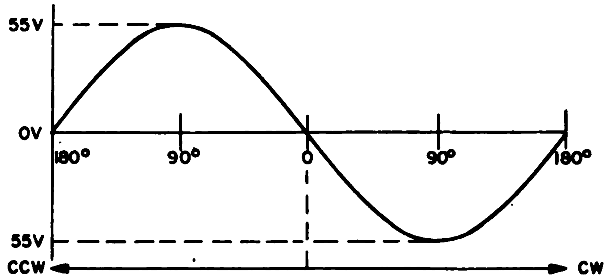
The rotor shaft of a CT is always turned by an external force, and produces varying output voltages from its rotor winding. Like synchro transmitters, the CT requires no inertia damper, but unlike either transmitter or receivers, rotor coupling to S2 is minimum when the CT is at electrical zero as shown in figure 2-2D.

RELATIONSHIP OF STATOR VOLTAGES TO THE RESULTANT MAGNETIC FIELD

When current flows in the stator circuits of a CT, a resultant magnetic field is produced. This resultant field can be rotated by the signal from a synchro transmitter, or synchro differential transmitter, in the same manner as the resultant stator field of the TDX previously considered. When the field of the CT stator is at right angles to the axis of the rotor winding, the voltage induced in the rotor winding is zero. When the stator field and the rotor's magnetic axis are aligned, the induced rotor voltage is maximum. Since the CT's output is expressed in volts, it is convenient to consider its operation in terms of stator voltages as well as in terms of the position of the resultant magnetic field, but it should be remembered that it is the ANGULAR displacement, with respect to the rotor axis, that determines the output of the CT.

RELATIONSHIP OF OUTPUT TO ROTOR POSITION

Figure 2-12 shows the amplitude and phase relation of the voltage output from a CT for one complete revolution of the rotor in each direction. The amplitude of the voltage varies sinusoidally from zero, where the rotor is at right angles to the stator flux, to a maximum of 55 volts at 90° displacement. (The outpu from a CT varies as the sine of the angle o the rotor displacement.)



175.10
Figure 2-12.—CT output voltage.

Voltages that are in phase with the suppl voltage are plotted above the reference lin (fig. 2-12), and voltages 180° out of phase with the supply are plotted below the reference line.

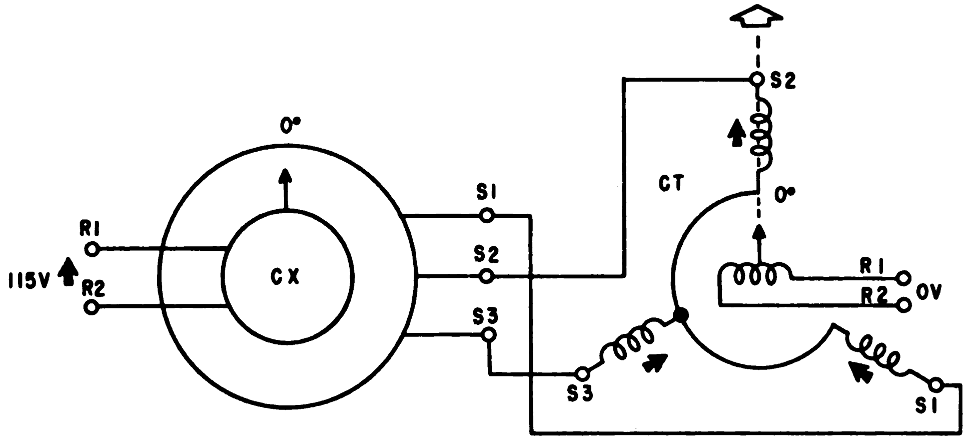
OPERATION OF THE CONTROL TRANSFORMER WITH A SYNCHRO TRANSMITTER

Consider the conditions existing in the system shown in figure 2-13, where a CT is connected for operation with a CX or CDX, and the rotors of both units are positioned at zero degrees. The relative phases of the individual stator voltages with respect to the R1 to R2 voltage of the transmitter are indicated by the small arrows. The resultant stator field of the CT is shown by the large arrow. With both rotors in the same position, the CT stator field is at right angles to the axis of the rotor coil. Since no voltage is induced in a coil by an alternating magnetic field perpendicular to its axis, the output voltage appearing across the rotor terminals of the CT is zero.

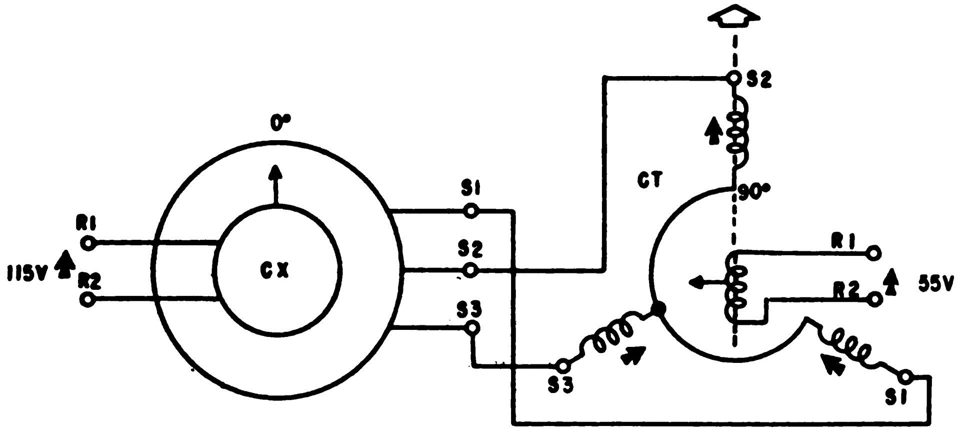
Now assume that the CT rotor is turned to 90 degrees, as in figure 2-14, while the CX rotor remains at zero degrees. Since the CT's rotor position does not affect stator voltages or currents, the resultant stator field of the CT remains aligned with S2. The axis of the rotor coil is now in alignment with the stator field. Maximum voltage, approximately 55 volts, is induced in the coil and appears across the rotor terminals as the output of the CT.

Next, assume the CX rotor is turned to 180 degrees, as in figure 2-15. The electrical positions of the CX and CT are 90 degrees apart, the CT stator field and rotor axis are aligned, and the CT's output is maximum again, but the direction of the rotor's winding is now reversed with respect to the direction of the stator field. The phase of the output voltage is therefore opposite to that of the CT in the preceding example. This means that the phase of the CT's output voltage indicates the direction in which the CT rotor is displaced with respect to the position-data signal applied to its stator.

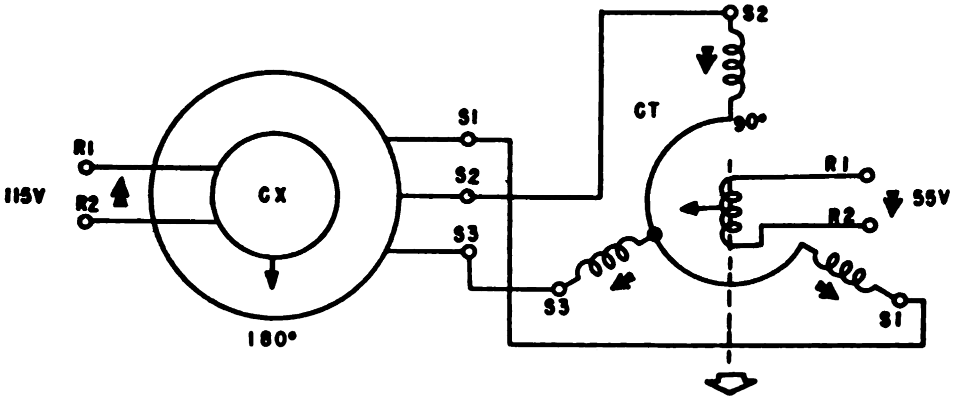
It is evident that the CT's output can be varied by rotating either its rotor or the position-



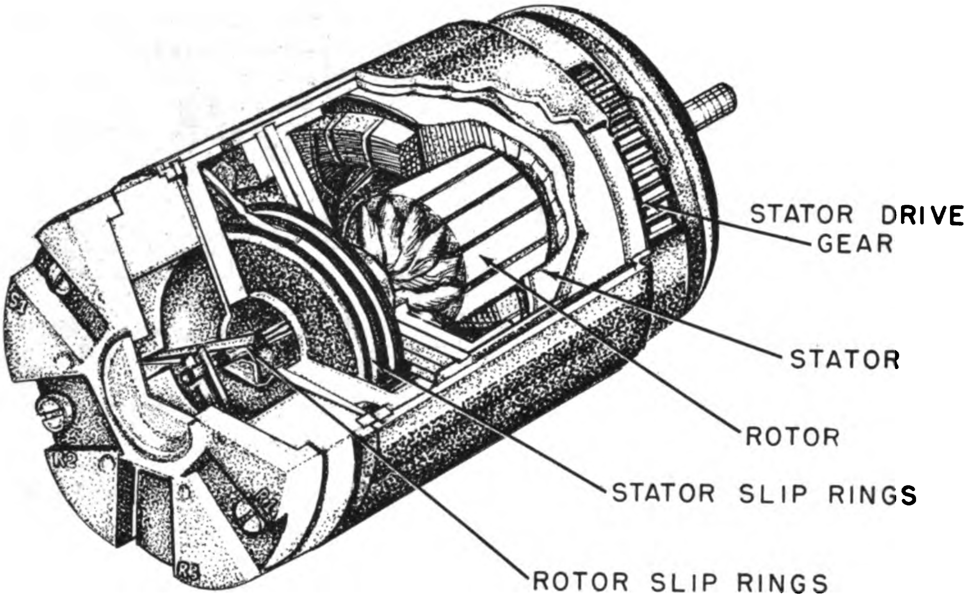
53.22(175)
Figure 2-13.—Conditions in CX-CT system with rotors in correspondence.



53.22
Figure 2-14.—Conditions in CX-CT system with CX rotor at 0° and CT rotor at 90°.



53.23
Figure 2-15.—Conditions in CX-CT system with CX rotor at 180° and CT rotor at 90°.



175.11

Figure 2-16.—Control transformer with rotatable stator.

data signal applied to its stator. It can also be seen that the magnitude and phase of the output depend on the relationship between signal and rotor rather than on the actual position of either.

Control transformers with a rotatable stator as shown in figure 2-16 are used in some control synchro systems. The rotatable stator eliminates the need for a differential synchro unit in applications where the CT output must reflect the resultant of two inputs.

As shown in figure 2-12, the output of a CT is also zero when the rotor is displaced 180° from the supply voltage. For proper operation in a control system, the CT and CX must function so that zero output represents zero displacement. The method for achieving this is discussed in a later chapter.

CHAPTER 3

SYNCHROS, PART II

This chapter continues the discussion on synchros and synchro systems. Multispeed synchro systems are briefly described, synchro capacitors and the standard connections relating to synchro systems are discussed, and the various methods of zeroing synchros are explained. In addition, other rotary electromechanical units which operate similarly to standard synchros, such as IC synchros, step motors, and resolvers are discussed.

MULTISPEED SYNCHRO SYSTEMS

If the input and output shafts of a synchro system rotate through equal arcs while the rotors of the transmitter and receiver in the system turn through equal arcs, the synchro system is a 1-speed system. If the data is transmitted at only one speed (whether the rotors turn through equal arcs or not) the system is a single-speed system.

Single-speed synchro systems do not provide sufficient accuracy in applications where the data to be transmitted covers a wide range of values. Increasing the speed of a single-speed system (from 1-speed to 36-speed for example) will provide greater accuracy. However, this is not usually done as the self-synchronous feature of the 1-speed system is lost. The number of positions in a single-speed synchro system in which the transmitter and receivers rotors can correspond is the same as the transmission speed. Thus, in a 36-speed system, there are 35 incorrect positions and one correct position of correspondence.

For accurate transmission of data without loss of self-synchronous operation, multispeed synchro systems are used. Multispeed synchro systems are those systems that use more than one speed of data transmission; thus, they require more than one output shaft. A dual speed system, for example, transmits data at two different speeds. Likewise, a tri-speed system transmits data at three different speeds.

Most multispeed synchro systems are dual-speed systems. Tri-speed systems, however, are used in some applications. To avoid confusion between terms such as 2-speed, dual-speed, 3-speed, and tri-speed, the speed of transmission in a synchro system should be referred to by the numerical ratio such as 1-speed, 2-speed, 36-speed, etc. and the number of speeds at which the data is being transmitted should be referred to as single-speed, dual-speed, or tri-speed.

DUAL-SPEED SYSTEM

The two speeds of a dual-speed synchro system are often referred to as the fast and slow, high and low, or more often as the fine and coarse.

A basic dual-speed synchro system consists of two transmitters and two receivers. One transmitter receives the external input to the system and, through a network of gears, passes the effects of the external input to the second transmitter. The gear ratio between these two transmitters determines the two specific speeds which the system will use to transmit the input data.

If, for example, the gear ratio between the two transmitters is 36:1, one revolution of the rotor of the first transmitter causes 36 revolutions of the rotor of the second transmitter. Thus, the first transmitter—the one which accepts the external input—can be called the coarse transmitter, and the second one can be called the fine transmitter. Representative speeds include 1 and 36, 2 and 36, and 2 and 72.

The output of each transmitter is passed through standard synchro connections to a receiver; hence, one receiver receives the coarse signal and the other one receives the fine signal. The two receivers may or may not be connected by a network of gears similar to the network between the two transmitters. In some dual-speed applications, a double receiver is used instead of two individual receivers.

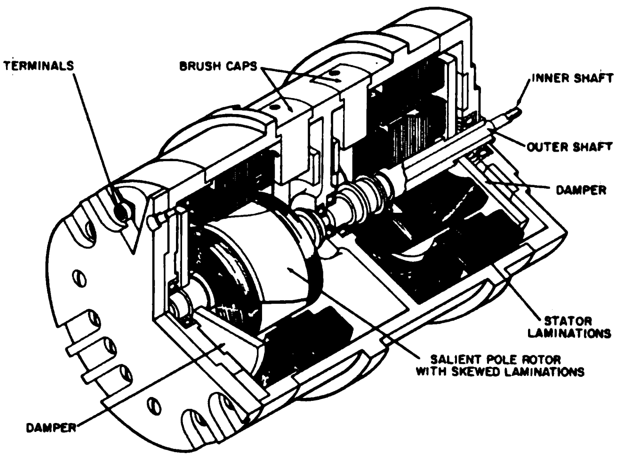
The double receiver (fig. 3-1) is a coarse and fine receiver enclosed in a common housing. It has a two-shaft output, one inside the other, and is similar in operation to the hour and minute hands of a clock. The hour hand corresponds to the coarse receiver, and the minute hand corresponds to the fine receiver. This double receiver has the advantage of requiring less space than two single receivers, but it also has a disadvantage in that when one receiver goes bad both must be replaced.

In a dual-speed synchro system, data is transmitted by the coarse transmitter while the system is far out of correspondence, and then shifted to the fine transmitter as the system approaches correspondence. This shifting from coarse to fine control is accomplished automatically through the use of synchronizing circuits as discussed in the next chapter.

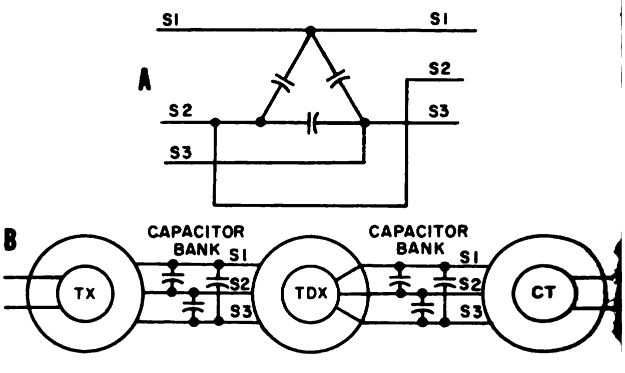
TRI-SPEED SYSTEM

The advent of long-range missiles and high-speed aircraft have brought about the need for accurately transmitting very large values. This is best done by a tri-speed synchro system.

A tri-speed synchro system transmits data at three different speeds as mentioned previously. These speeds are sometimes referred to as coarse, medium or intermediate, and fine. A tri-speed synchro system for transmitting range in a weapons system, for example, might reduce the value of range into miles, 10,000 yards, and 2000 yards. By providing the range value in three different scales greater accuracy is obtained than would be possible with a dual-speed system. Representative speeds for tri-speed systems include 1, 36, and 180; 1, 36, and 360; and 1, 18, and 648.



175.12
Figure 3-1.—Cutaway view of a double receiver.



12.279
Figure 3-2.—Synchro capacitors.

SYNCHRO CAPACITORS

In a circuit where a transmitter is supplying a signal to a differential unit or control transformer, the transmitter is supplying a lagging current to the stator of the differential unit or control transformer. To minimize the amount of current lag and, thereby, improve the accuracy of the system, a capacitive network is placed in the circuit. This network is generally termed a synchro capacitor, even though the network contains three individual capacitors and the total capacitance of all three capacitors is the rated value of the network. The three capacitors are delta connected as shown in figure 3-2A and are connected in parallel with the stator windings of the differential unit and CT (fig. 3-2B). The connections are made as short as possible, as high currents in long leads increase the transmitter load and reduce the system accuracy.

Synchro capacitors decrease the line current drawn by synchro systems and, in effect, increase the torque of the synchro receivers in the system. This effective increase in torque near the point of synchronization increases the accuracy of the overall system.

Currents present in the stator circuits of a TX-TR synchro system are a result of a voltage difference between the stators. If the synchros e in correspondence there is no voltage dif- rence and hence no current in the stator cir- uits. Therefore, capacitors are not required in TX-TR synchro system.

STANDARD CONNECTIONS

In systems where many synchro units are sed, it is necessary to have a clearly defined et of standard connections. The connections escribed below are usually followed unless ere is a good reason for doing otherwise.

The standard markings and connections for e five wires of a synchro system are shown figure 3-3. (In practice, any letter may be sed.) The "B" in figure 3-3 indicates any ingle-letter bus and "BB" any double-letter us. Rotor lead R1 is connected to the single- etter bus, R2 to the double-letter bus, S1 to e low-numbered bus, S2 to the middle, and S3 o the high-numbered bus.

An increasing reading is being sent over the ires of a synchro system when the numerical alue of the information being transmitted is ncreasing. Synchros turn CCW for an increasing eading in most systems.

ONNECTIONS FOR MULTISPEED YSTEMS

In multispeed synchro systems, the wires or the lowest speed are numbered 1, 2, and 3 or the next higher speed 4, 5, and 6 etc. The arkings and connections for a dual-speed sys- em are shown in figure 3-4.

CONNECTIONS FOR TRANSMITTERS AND RECEIVERS

The standard connections for CW and CCW rotation for a TX are shown in figure 3-5A. Figure 3-5B shows the connections for the TR.

The TDX is connected as shown in figure 3-6A. The connections at the top of figure 3-6A will cause the TDX (with constant stator voltages) to transmit an increasing reading from its rotor leads when the shaft is turned CW. For an increasing reading when the shaft is turned CCW, the TDX is connected as shown at the bottom of figure 3-6A.

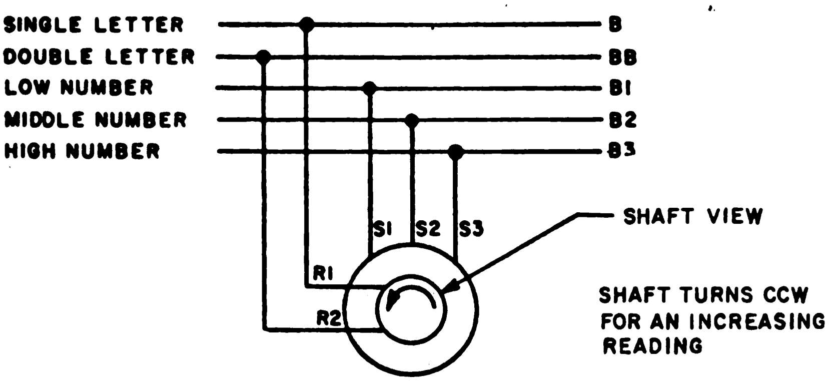
Standard connections for the TDR are shown in figure 3-6B.

CT CONNECTIONS

The stator leads of a CT are connected as shown at the top of figure 3-7, if the CT rotor is to turn CCW to approach zero output after receiving an increasing reading on the stator leads. If the rotor is to turn CW to approach zero output, the CT is connected as shown at the bottom of figure 3-7.

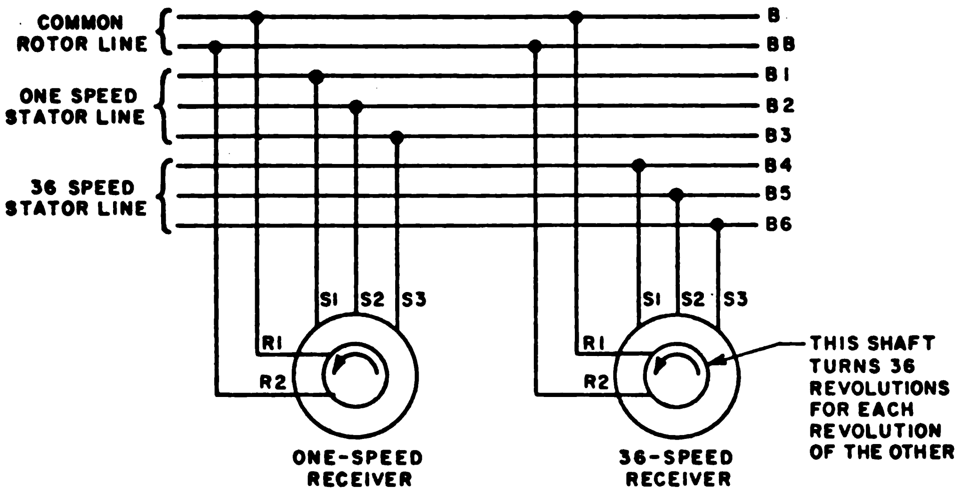
ZEROING SYNCHROS

For synchros to function properly in a system, they must be correctly connected and aligned in respect to each other and to the other devices with which they are used. Electrical zero is the electrical reference point for alignment of all synchro units. The mechanical reference point for the units connected to the syn-



175.13

Figure 3-3.—Standard synchro wire designations.



175.14
Figure 3-4.—Standard connections for dual-speed synchro system.

chros depends upon the particular application of the synchro system. For example, when a synchro system is used to repeat ship's course data, the mechanical reference point would be true north. For radar or sonar equipments, it could be the ship's bow or zero degrees. In a range or azimuth data transmission system, a specific distance or angle could be the reference point. Whatever the system, the electrical and mechanical reference points must be aligned.

ELECTRICAL ZERO

As explained in chapter 2, for any given rotor position of a synchro, there is a definite set of stator voltages.

Each type of synchro has a combination of rotor position and stator voltages which is called its electrical zero. The electrical zero condition is the reference point for the alignment of the synchro.

Chapter 2 defined the electrical zero as the condition in which the axis of the rotor is lined up with the axis of the S2 winding. Looking back at figure 2-4, you can see that two such positions 180° apart are possible. As shown in the diagram, the rotor is at the electrical zero position, but if it were turned 180° we could still say it is lined up with the S2 winding.

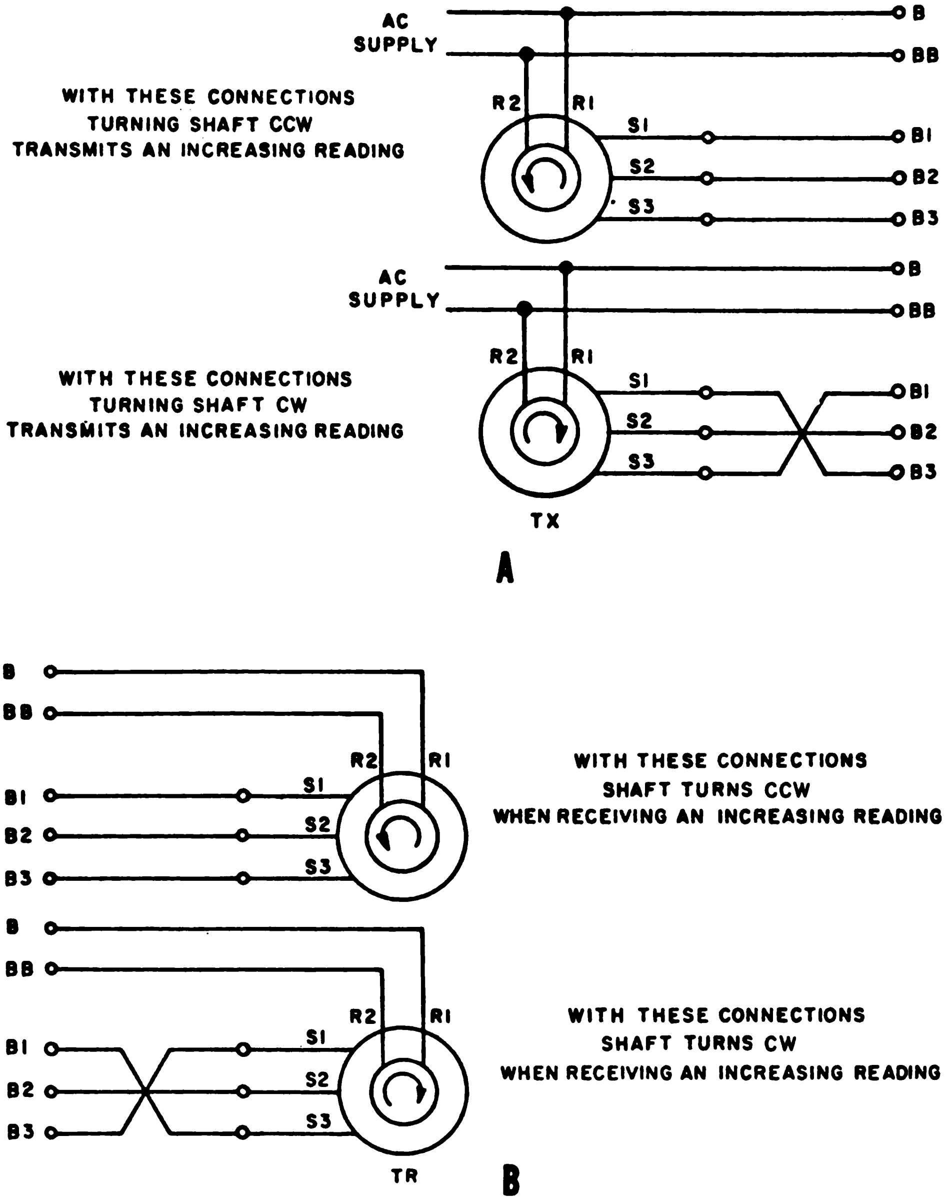
In both the 0° position and the 180° position, the terminal voltage between S1 and S3 is zero. However, in the 0° position the voltages from S2 to S3 or from S2 to S1 are IN PHASE with the voltage from R1 to R2, while in the 180° rotor position the voltage from S2 to S3 (or S1) is 180° out of phase with the rotor voltage.

The electrical zero position is therefore completely defined as the position of the rotor in which the voltage between S1 and S3 is zero, and the voltage from S2 to S3 is in phase with the voltage from R1 to R2.

A synchro transmitter (CX or TX) is properly zeroed if electrical zero voltages exist when the unit whose position the CX or TX transmits is set to its mechanical reference position. A synchro receiver (TR) is properly zeroed if, when electrical zero voltages exist, the device actuated by the receiver assumes its mechanical reference position. In a receiver or other unit having a rotatable stator, the zero position is the same, with the added provision that the unit to which the stator is geared is set to its reference position. The terminal-to-terminal voltages for 115 and 26 volt synchros at electrical zero are as follows:

115-VOLT SYNCHROS		26-VOLT SYNCHROS	
R1 to R2	115 volts	R1 to R2	26 volts
S2 to S1	78 volts	S2 to S1	10.2 volts
S2 to S3	78 volts	S2 to S3	10.2 volts
S1 to S3	zero volts	S1 to S3	zero volts

A differential synchro unit is zeroed if the unit can be inserted into a system without introducing a change in the system. In the electrical


AC SUPPLY
B
BB
WITH THESE CONNECTIONS TURNING SHAFT CCW TRANSMITS AN INCREASING READING
R2
R1
S1
S2
S3
B1
B2
B3
AC SUPPLY
B
BB
WITH THESE CONNECTIONS TURNING SHAFT CW TRANSMITS AN INCREASING READING
R2
R1
S1
S2
S3
B1
B2
B3
TX
A
B
BB
R2
R1
B1
B2
B3
S1
S2
S3
WITH THESE CONNECTIONS SHAFT TURNS CCW WHEN RECEIVING AN INCREASING READING
B
BB
R2
R1
B1
B2
B3
S1
S2
S3
WITH THESE CONNECTIONS SHAFT TURNS CW WHEN RECEIVING AN INCREASING READING
TR
B

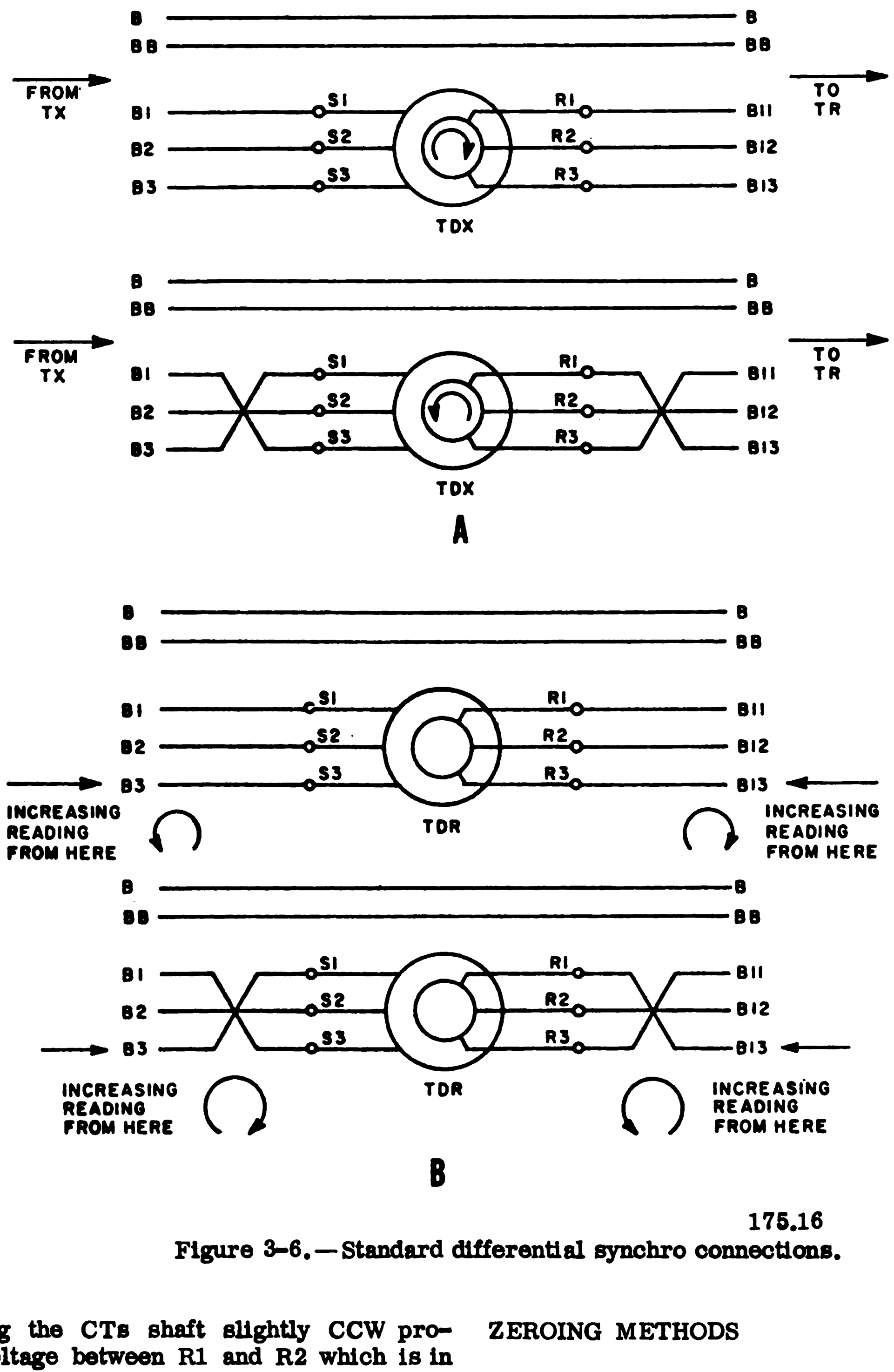
175.15

Figure 3-5.—Standard transmitter and receiver connections.

zero position the axes of coils R2 and S2 are at zero displacement. Terminal voltages for differential units are as follows:

115-VOLT SYNCHROS	26-VOLT SYNCHROS
R1 to R3 zero volts	R1 to R3 zero volts
S1 to S3 zero volts	S1 to S3 zero volts
R3 to R2 78 volts	R3 to R2 10.2 volts
S3 to S2 78 volts	S3 to S2 10.2 volts
R2 to R1 78 volts	R2 to R1 10.2 volts
S2 to S1 78 volts	S2 to S1 10.2 volts

A synchro control transformer is properly zeroed if its rotor voltage is minimum when electrical zero voltages are applied to its stator,

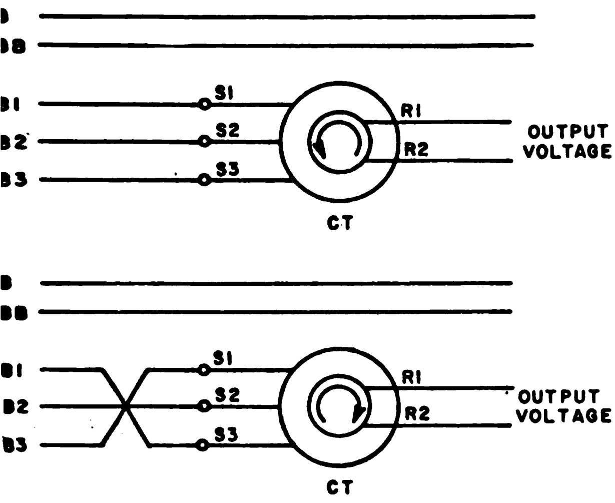


175.16
Figure 3-6.—Standard differential synchro connections.

and turning the CTs shaft slightly CCW produces a voltage between R1 and R2 which is in phase with the voltage between R1 and R2 of the CX or TX supplying excitation to the CT stator. Electrical zero voltages for the stator only, are the same as for transmitters and receivers.

ZEROING METHODS

There are various methods for zeroing synchros. The procedure used depends upon the facilities and tools available and how the synchros are connected in the system. Also, the procedure



175.17

Figure 3-7.—Standard control transformer connections.

or zeroing a unit whose rotor or stator is not ree to turn may differ from the procedure for zeroing a similar unit whose rotor or stator is ree to turn.

Voltmeter Method

The most accurate method of zeroing a synchro is the a.c. voltmeter method. The procedure and the test-circuit configuration for this method vary somewhat, depending upon which type of synchro is to be zeroed. Transmitters and receivers, differentials, and control transformers each require different test-circuit configurations.

An electronic or precision voltmeter having a 0- to 250-volt and a 0- to 5-volt range should be used. On the low scale the meter should be able to measure voltages as low as 0.1 volt.

There are two major steps in the zeroing procedure of a synchro. First, the coarse or approximate setting is determined, and, second, the fine setting is made. The coarse adjustment is a check between the correct setting and a setting 180° out. Recall from the discussion of electrical zero that the difference between the two positions determines the phase relation between the voltages on S2 to S1 (or S3) and on R1 and R2. The voltages are in phase when the rotor is at its electrical zero position, and 180° out of phase when the rotor position is 180° away from electrical zero. Hence the coarse check provides a means to determine the phase relation between the supply voltage and the induced voltages in the S2 and S1 stator windings.

Standard synchros have an arrow stamped on the stator frame and a reference line scribed on the rotor shaft, as shown in figure 3-8. With the synchro input on zero or the reference value, the alignment of the arrow and the line on the rotor will set the synchro on approximate zero. Thus, with standard synchros, this is the coarse check.

ZEROING TRANSMITTERS AND RECEIVERS.—Control transmitters, torque transmitters, and receivers are functionally and physically similar. Therefore, they are zeroed in the same manner. The zeroing procedure is broken down into steps as follows.

1. Carefully set the quantity whose position the synchro transmits to its zero or mechanical reference position.
2. Deenergize the synchro circuit and disconnect the stator leads. Set the voltmeter to its 0- to 250-volt scale and connect it into the synchro circuit as shown in figure 3-9A. Many synchro systems are energized by individual switches, therefore be sure that the synchro power is off before working on the connections.

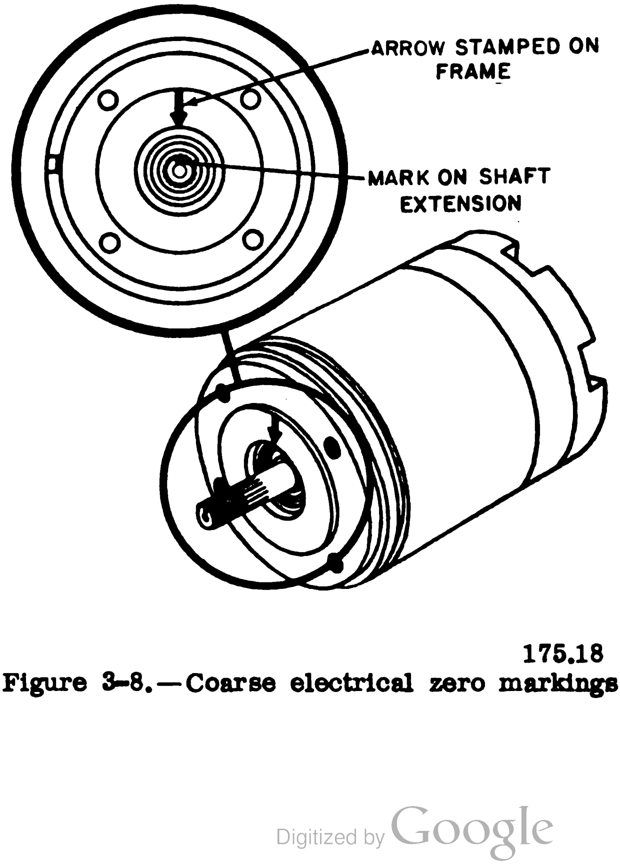


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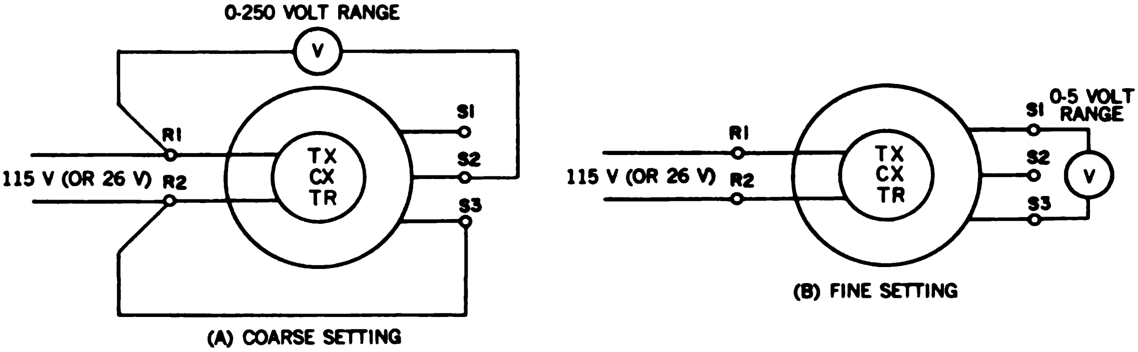
Figure 3-8.—Coarse electrical zero markings.



(A) COARSE SETTING

(B) FINE SETTING

53.26

Figure 3-9.—Zeroing a transmitter or receiver by the voltmeter method.

3. Energize the synchro circuit and turn the stator or rotor until the meter reads about 37 volts (15 volts for 26-volt synchros). This is the coarse setting and places the synchro approximately on electrical zero.

4. Deenergize the synchro circuit and connect the meter as shown in figure 3-9B, using the 0 to 5 volt scale.

5. Reenergize the synchro circuit and adjust the rotor or stator for a null (minimum voltage) reading. This is the electrical zero position.

A simple check on the common electrical zero position of a TX-TR synchro system can be done with a jumper. Put the transmitter and receiver on zero and intermittently jumper S1 and S3 at the receiver. The receiver should not move. If it does, the transmitter is not on zero and should be rechecked.

ZEROING DIFFERENTIAL SYNCHROS.—To zero differential synchros by the voltmeter method proceed as follows:

1. Set the unit concerned accurately to its zero or mechanical reference position.

2. Remove all other connections from the differential leads, set the voltmeter on its 0- to 250-volt scale, and connect as shown in figure 3-10A. If a 78-volt supply is not available, 115 volts may be used. If 115 volts are used instead of 78 volts, do not leave the unit connected for more than two minutes or it may overheat.

3. Unclamp the differential and turn it until the meter reads minimum. The differential is now on appropriate electrical zero. Deenergize and reconnect as shown in figure 3-10B.

4. Set the voltmeter on the 0- to 5-volt scale, and turn the differential transmitter until a null (minimum voltage) reading is obtained. Clamp the differential in this position deenergize and reconnect all leads for normal operation.

ZEROING A CT.—To zero a CT by the voltmeter method remove the connections from the CT and reconnect as shown in figure 3-11A. Turn the rotor or stator to obtain a minimum voltage reading, then reconnect the meter as shown in figure 3-11B. Adjust the rotor or stator for a null reading, clamp the CT in position and reconnect all leads to their original position.

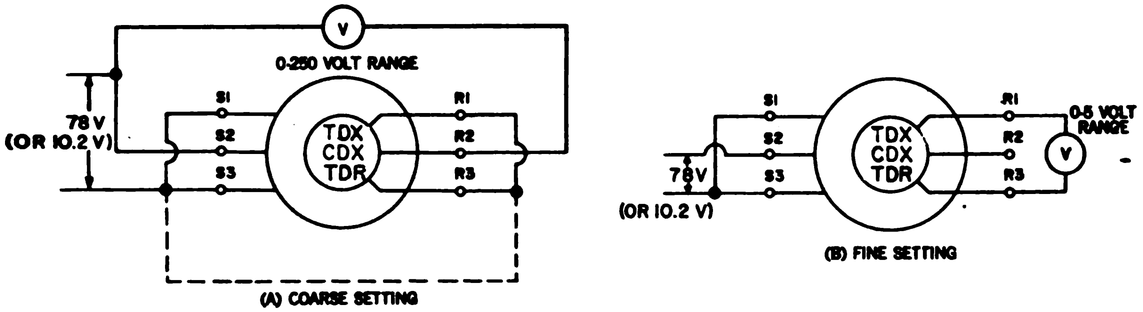
Electrical Lock Method

The electrical lock method (although not as accurate as the voltmeter method) is perhaps the fastest method of zeroing synchros. This method can only be used however, provided the rotors of the units are free to turn and the lead connections are accessible.

To zero a synchro by the electrical lock method, deenergize the unit, connect the leads, and apply power as shown in figure 3-12. The synchro rotor will then quickly snap to the electrical zero position and lock. As stated previously, 115 volts may be used as the power supply instead of 78 volts provided that the unit does not remain connected for more than two minutes.

ZEROING MULTISPEED SYNCHRO SYSTEMS

If a fine and a coarse synchro are used to define a quantity's position, the synchros must

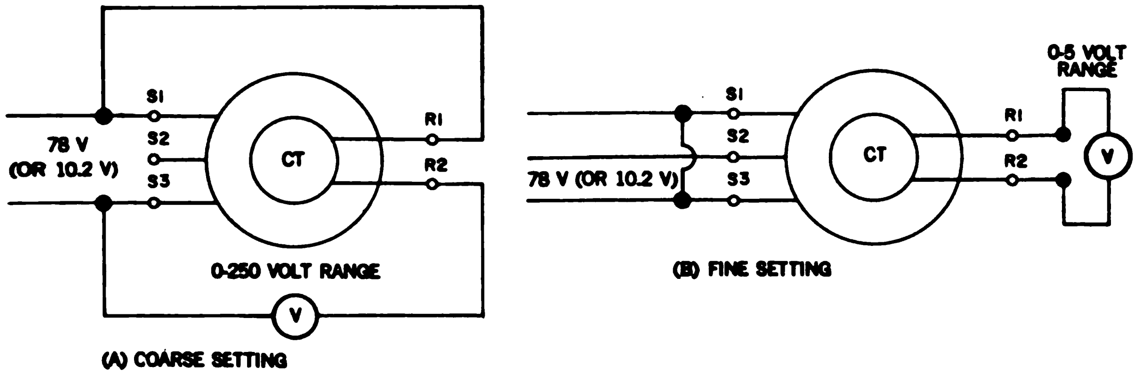


(A) COARSE SETTING

(B) FINE SETTING

1.121(53)A

Figure 3-10.—Zeroing differential synchros by the voltmeter method.



(A) COARSE SETTING

(B) FINE SETTING

53.36

Figure 3-11.—Zeroing a control transformer by the voltmeter method.

be zeroed together. As pointed out earlier, the coarse synchro will define the position of a quantity to within the range of the fine synchro's capability to define the position more precisely. From this you can reason that the coarse synchor provides the first significant figure in the numerical description of the quantity's position. Obviously then the coarse synchro is zeroed first. When zeroing the synchros in a system you can consider each synchro as an individual unit. Thus one of the methods already described can be used to zero the coarse synchro.

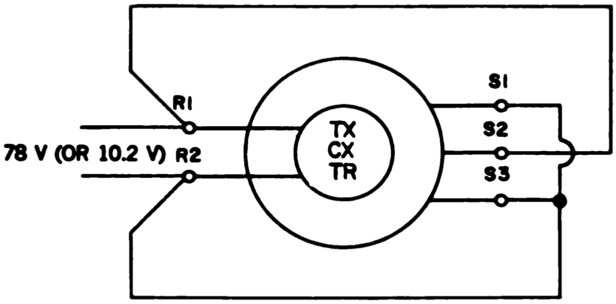
The next step after the coarse synchro is zeroed is to zero the fine synchro. A fine synchro provides the next significant figure in the numerical description of the quantity's position. The fine synchro is zeroed as an individual unit. But the quantity's zero or reference position has already been established with respect to the coarse synchro's electrical zero position. Hence when you zero a fine synchro the setting of the coarse synchro and the quantity must be set together.

There are a few three-speed synchro systems. These systems are zeroed in the same manner as the dual-speed systems. First, establish the zero position for the synchro which provides the most significant figure, and work down to the least significant figure. Remember that all the synchros in a system must have a common electrical zero position.

SYNCHRO TESTERS

Synchro testers of the type shown in figure 3-13 are used primarily for locating a defective synchro. They also provide a fairly accurate method of setting synchros on electrical zero.

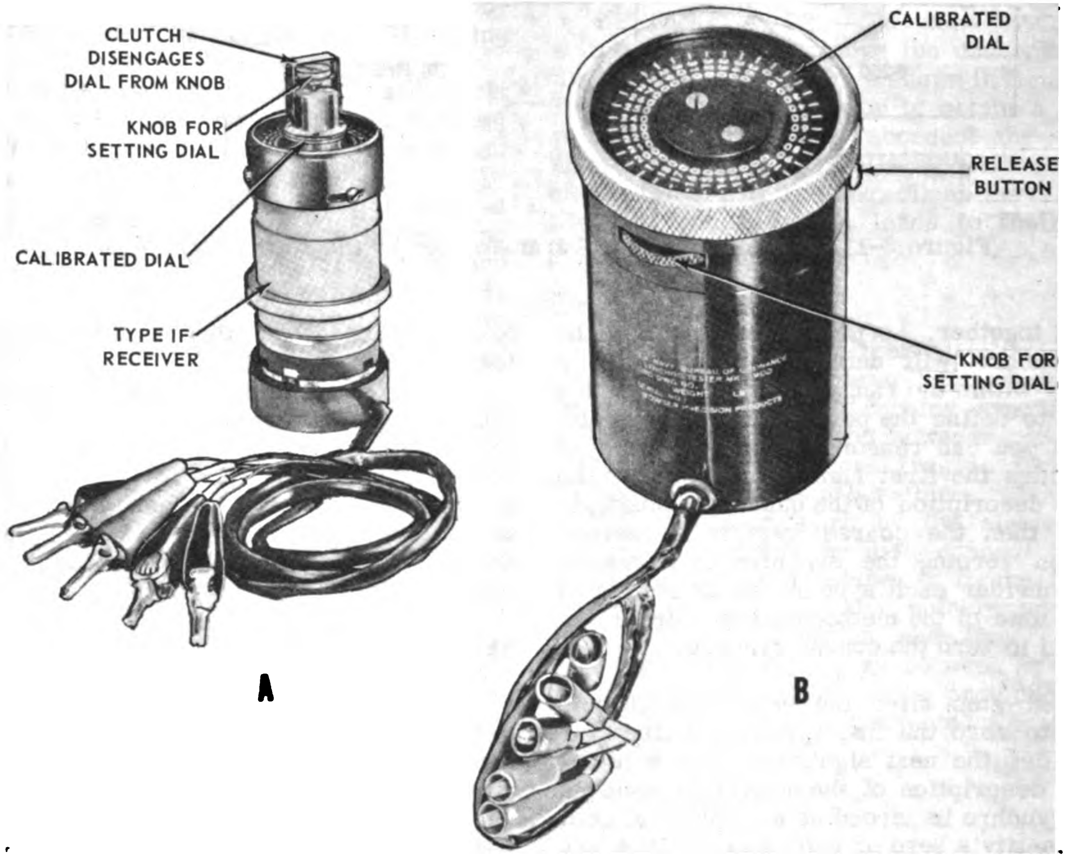
To zero a synchro with the tester, connect the units as shown in figure 3-14 and turn the synchro until the tester dial reads 0 degrees. This is the approximate electrical zero position. Momentarily short S1 to S3 as shown. If either



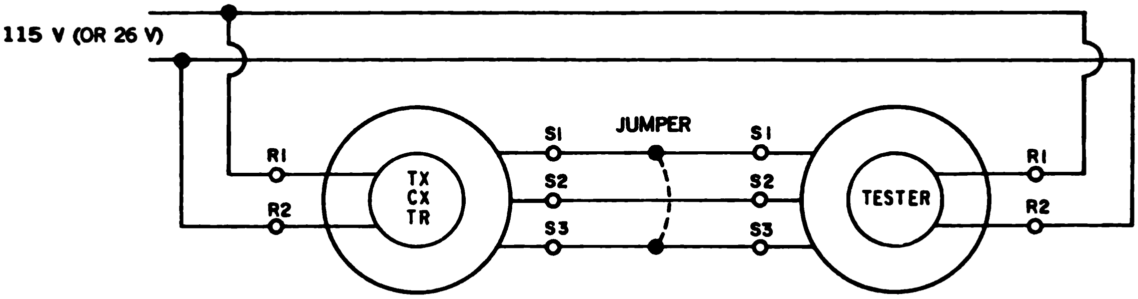
53.30
Figure 3-12.— Zeroing a synchro by the electrical lock method.

the synchro or tester dial moves, the synch is not accurately zeroed, and should be shift slightly until there is no movement when S1 a S3 are shorted.

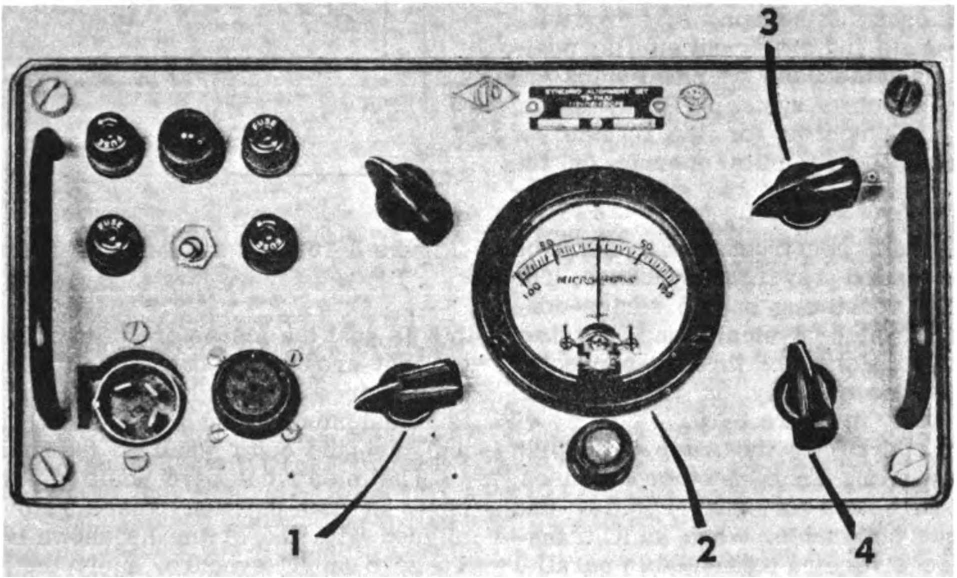
The synchro alignment set (fig. 3-15) is portable, general purpose test set used to che the alignment of synchros or resolvers. It c be used to align any 400-Hz synchro or r solver. In addition to its higher sensitivity, t test set has an additional advantage over t methods previously discussed in that the te set can also supply excitation voltage for t synchro or resolver being aligned. (Resolver are discussed later in this chapter.)



175.19
Figure 3-13.—Synchro testers, (A) 60-Hz; (B) 400-Hz.



53.28
Figure 3-14.—Zeroing a synchro using a synchro tester.



1. EXCITATION SWITCH.
2. MICROAMMETER.
3. METER SENSITIVITY SWITCH.
4. FUNCTION SWITCH.

175.20
Figure 3-15.—Synchro alignment set.

The test set basically consists of a bandpass amplifier and power supply, a synchro or resolver excitation supply with outputs from 3 to 115 volts rms (1, fig. 3-15) and switching circuits. The output voltages from the synchros or resolvers are applied to the amplifier, the output of which is fed to a phase sensitive detector circuit. The detector's output is metered by the microammeter (2). A meter switch (3) selects the meter sensitivity from 300 volts full scale to 0.1 volt full scale, plus a calibrate and off position.

The meter has a ZERO·center scale and indicates 0 when the synchro or resolver is adjusted to either of its two nulls. The synchro or resolver is adjusted to a null position with the function switch (4) in the ZERO position. When the null is reached, the function switch is switched to the POL position and note is taken of the meter reading. Then the function switch is returned to ZERO position and the synchro is rotated 180° to its opposite null. When the opposite null is reached, the function switch is again switched to the POL position and a note made of the reading. The correct null will be the one indicating the lowest reading with the function switch in the POL position. When the synchro is adjusted to this null, it is electrically zeroed with the correct polarity.

SIMILAR DEVICES

Other electromagnetic devices similar to synchros are used in various shipboard and aircraft applications. Among these devices are IC synchros, step motors, and resolvers.

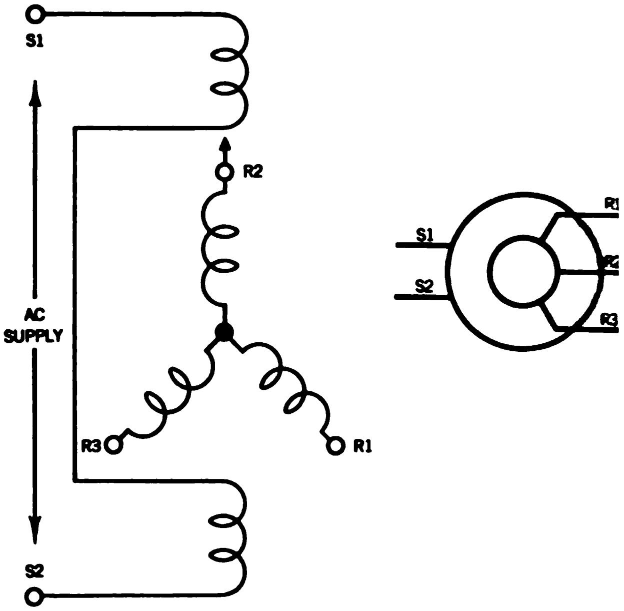
IC SYNCHROS

The engine order telegraph, steering telegraph, rudder angle indicator and similar position-indicating systems used on naval ships are usually simple synchro systems. Many ships, however, use IC synchros for the transfer of such information. These units operate on the same general principles as the synchros discussed previously.

Because of their construction, IC synchros are sometimes called reversed synchros. The primary winding, consisting of two series-connected coils, is mounted physically on the stator. The secondary, consisting of three y-connected coils, is mounted physically on the rotor as shown schematically in figure 3-16.

IC synchros operate on the same principles of interacting magnetic fields as other synchros, but differ in direction of shaft rotation and amount of torque obtainable. When an IC transmitter and IC receiver are connected in parallel (fig. 3-17A), the shaft of the IC receiver follows the rotation of the IC transmitter shaft. In figure 3-17B, the IC transmitter is replaced by a synchro transmitter; the IC receiver shaft now turns in a direction opposite to that of the synchro transmitter. Voltages which cause CCW rotation of a synchro shaft cause CW rotation of an IC unit shaft. An IC receiver can be connected to an IC transmitter so that the shafts rotate in opposite directions. These connections are shown in figure 3-17C. For a synchro receiver to follow the rotation of an IC transmitter, they must be connected as shown in figure 3-17D.

The torque obtainable from either an IC unit or synchro is determined by the magnetizing power, which is limited by the allowable temperature rise. When the stator is energized, as in IC units, the magnetizing power can be increased with a resulting larger torque. The reason for this is that the losses are dissipated in the form of heat around the outer shell of the IC transmitter or receiver. In synchros, this heat loss is dissipated through the rotor, the air gap, and then the outer shell to the surrounding air.



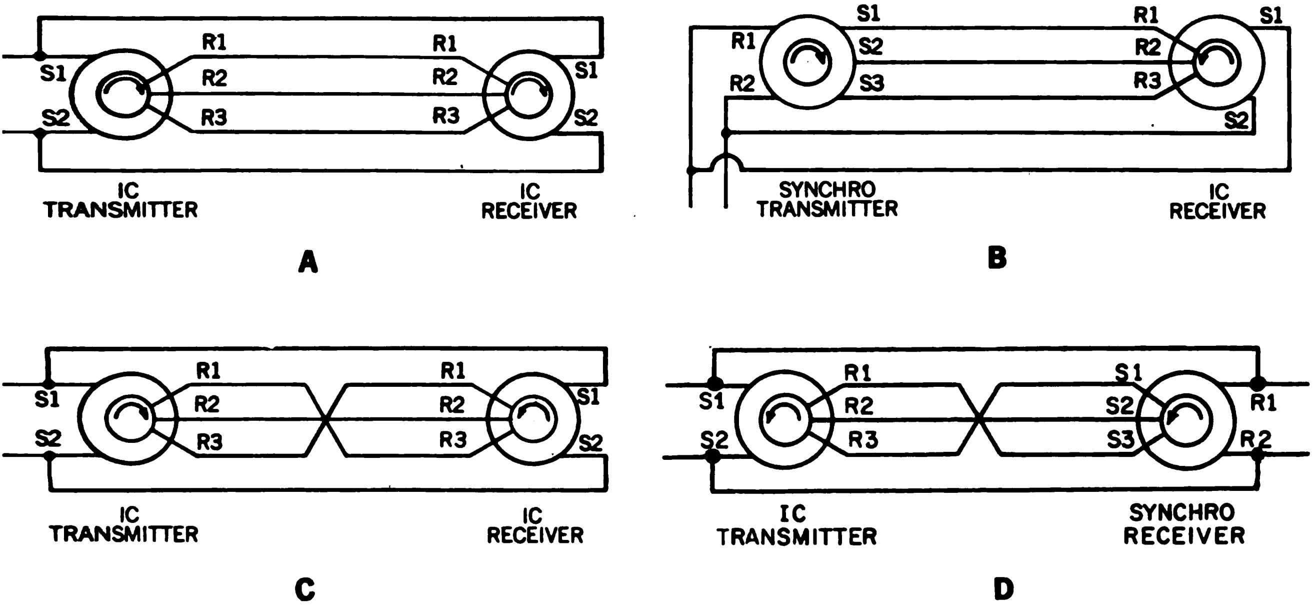
175.21
Figure 3-16.—IC synchro schematic diagrams.

The electrical zero position for an IC synchro is the position where rotor coil R2 is aligned with the stator as shown in figure 3-16. To zero an IC synchro, apply the same general theory as described for other synchros.

STEP TRANSMISSION SYSTEM

All of the synchro units discussed thus far operate on alternating current. In applications where alternating current is not available, there is a need for systems similar to synchro systems which operate on direct current. The step transmission system (sometimes referred to as the step-by-step system) is such a system.

In the step transmission system a step transmitter and a step motor are used together to transmit angular motion between remote locations. The shaft of the step transmitter is rotated and periodically switches a d.c. excitation voltage from one pair of coils to another in the step motor. The step motor, which is the receiver

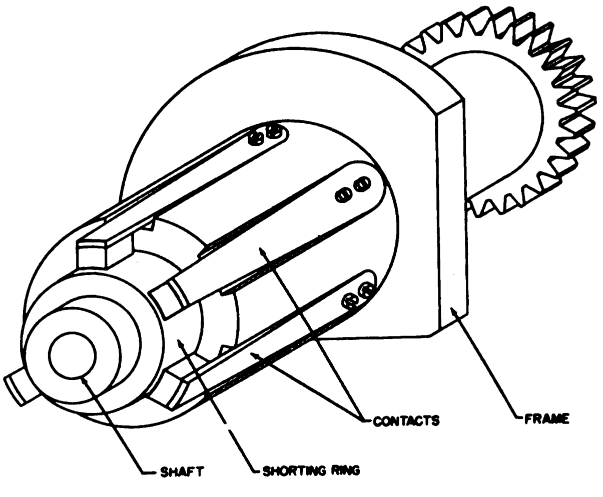


175.22
Figure 3-17.—IC vs standard synchro connections.

the system, responds to this varying excita-on by rotating an amount that is proportional the transmitter's motion.

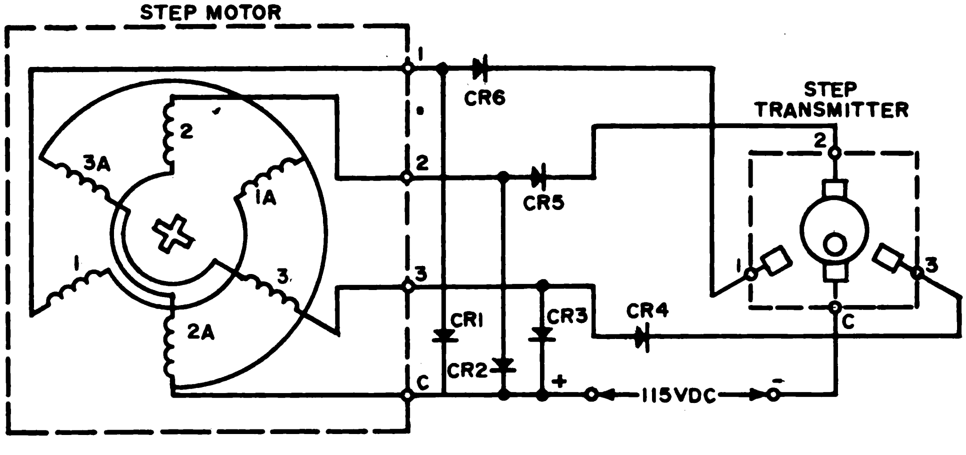
The step transmitter (fig. 3-18), has an in-ulated frame, a shaft, an eccentrically mounted horting ring, and four contacts. The shorting ring s surrounded by the four contacts, which are astened to the ends of flat, conducting spring rms. Each spring is secured in a slot in the nsulated frame. During a complete revolution f the step transmitter's shaft, brushes 1, 2, nd 3 come in contact with the shorting ring n a sequence. But brush C is in contact with he shorting ring at all times. One side of the .c. supply voltage is connected through brush C to the shorting ring. As the shaft is rotated, ne side of the supply voltage is connected to he other brushes in a definite order.

The stator of the step motor has six field coils spaced 60 degrees apart. The coils are connected in three groups of two coils each (fig. 3-19), with opposite coils being connected in series. One end of each pair of coils is connected to one of the brushes in the step transmitter. The other end of the coils is connected to the other side of the d.c. supply voltage through a common lead. As the rotor of the step transmitter is turned, the circuit to the field coils in the step motor are energized in sequence producing a rotating step-by-step stator field. Thus, the motor rotates in increments or steps rather than smoothly.



166.8
Figure 3-18.—Step transmitter.

The rotor of the step motor is made of soft iron and has four projections in the form of a cross along its length. As the stator field rotates,



166.8
Figure 3-19.—Interconnections for a step motor and a step transmitter.

the field's lines of flux cause the rotor to turn so as to provide a path of least reluctance for the magnetic field. Figure 3-20 graphically illustrates the sequence of the steps, while table 3-1 lists the steps and the conditions that exist during a complete revolution of the step transmitter. Note that the step motor's rotation is only a quarter of the step transmitter's rotation.

Diodes are used with the step motor as spark suppressors, (fig. 3-19). Diodes CR1, CR2, and CR3 act as a short circuit when a voltage is produced opposite to that applied to the coils of the step motor. If the coils of the step motor produce a voltage larger than that applied, diodes CR4, CR5, and CR6 appear open.

A step transmission system is not self-synchronous and its limited number of steps does not permit a quantity to be transmitted smoothly. This type of transmission system is cheap, rugged, and relatively powerful. It is used where exact linear transmission is not required.

RESOLVERS

A resolver is a rotary electromechanical device whose output is a trigonometric function of its input. Physically, resolvers are similar to synchros. They are classified according to size (diameter) in the same manner and they may be mounted with most standard synchro mounting hardware. A cutaway view of a resolver is shown in figure 3-21.

The stator of the resolver (fig. 3-21), is a cylindrical structure of slotted laminations on which two coils are wound. The rotor is composed of a shaft, laminations, 2 windings, and 4 slip rings. Compensator components, which improve the angular accuracy of resolvers, may consist of resistors or additional windings in the stator and rotor winding circuits. Compensator windings, which increase the accuracy of the resolver, are located inside the stator. Compensating (calibrating) resistors, which compensate for voltage inaccuracies and phase shifts, may be mounted either inside or outside the resolver housing.

A cylindrical frame with a standardized mounting flange houses the assembled resolver. External connections can be made to an insulated terminal board on the rear of the housing. Internal connections of the rotor and stator are terminated at the terminal board. Miniature resolvers often have unterminated lead wires brought out through the rear of the resolver, eliminating the need for a terminal block. A reference line is scribed on the face of the housing, for alignment with a similar line on the end of the rotor shaft, to determine coarse electrical zero.

Theory of Operation

Basically, a resolver is a transformer in which the secondary windings can be rotated with respect to the primary windings. Consequently the amount of magnetic coupling between the primary and the secondary is variable. In its most common form it consists of a stator and a rotor, each having two separate windings aced precisely at right angles to each other ig. 3-22). Most schematic diagrams of reolvers show only the active windings, therere, if three windings are used in a particular pplication, the diagram will show these three.

Since the two stator windings are physically nd electrically at right angles to each other, an a.c. voltage is applied to the windings there ould be no magnetic coupling between them. he stator windings are mounted on the resolver ousing and are stationary with respect to it.

The rotor windings of the resolver are wound t right angles to each other. Hence there is no agnetic coupling between the two windings. he rotor windings are mounted on the rotor haft and will turn with it. The rotor is capable f unlimited rotation. Thus the rotor windings an be set at any angle with respect to the stator indings.

A resolver has both electrical and mechanial (rotation) inputs. The outputs will be proortional to the product of the electrical input nd either the sine or cosine of the angle through hich the rotor has been turned. Figure 3-23 shows the rotor in three different positions with respect to the stator. The stator is supplied with a fixed voltage which is assumed to be unity. Since similar action takes place in all the windings only one set is shown for clarity.

In figure 3-23A, the rotor and stator windings have an angle of 0° between them. With the rotor in this position, all the flux established by the stator winding voltage cuts the rotor winding and the voltage induced in the rotor is maximum. For example, with a turns ratio between the stator and rotor of 1:1 and an input voltage of 1 volt, ignoring the small transformer losses, the output voltage will be 1 volt.

In figure 3-23B, the rotor is turned so that the two windings are displaced by 30 degrees. Now only a part of the stator flux cuts the rotor winding, and the voltage induced in the rotor is 0.866 volts.

In figure 3-23C, the rotor is turned so that the two windings are displaced by 90 degrees. At this angle there is no magnetic coupling between the windings, and the output voltage is zero.

166.10
Table 3-1.—Step-by-step system operation

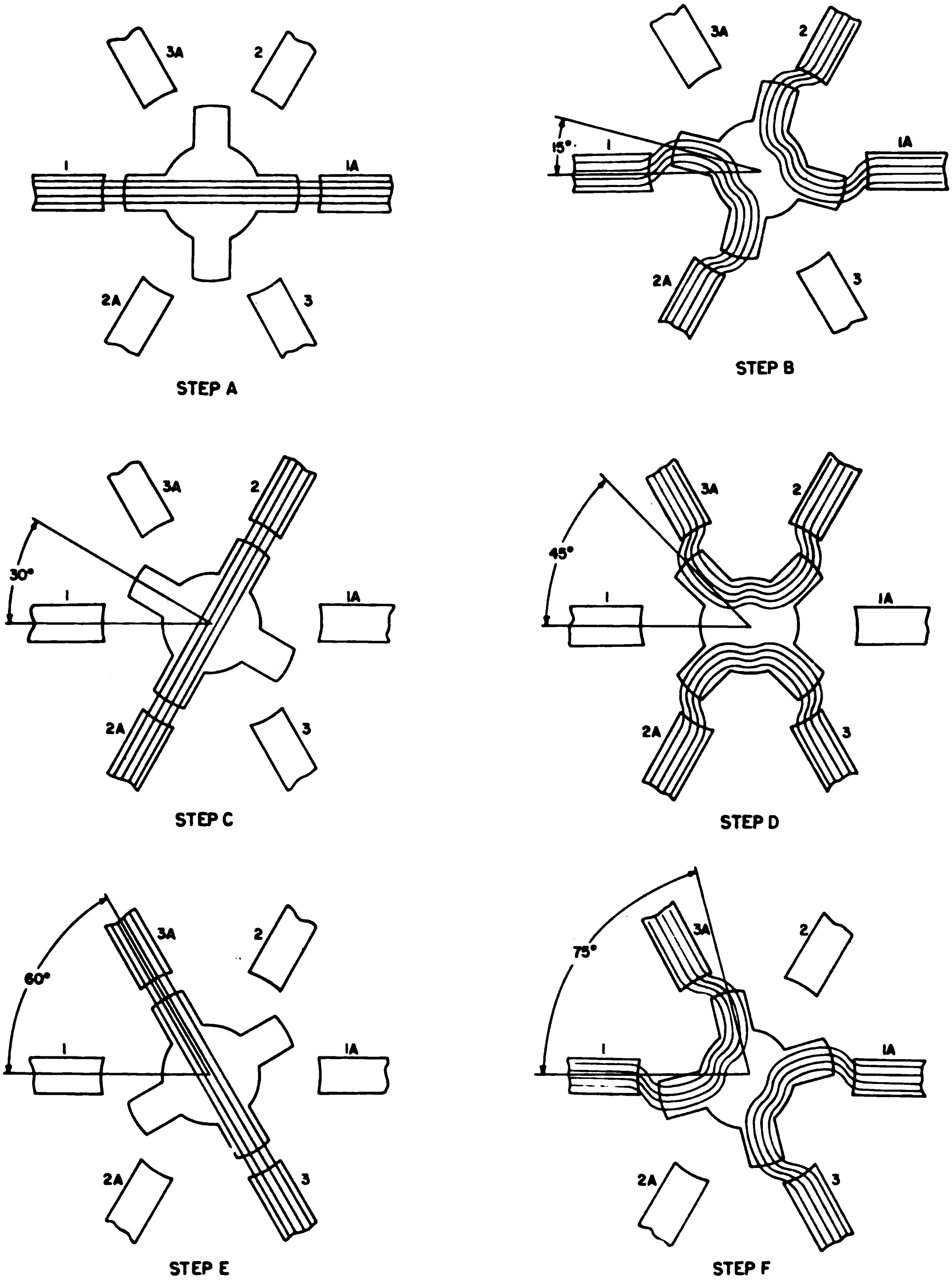
Steps	Degrees of Transmitter Rotation	Contacts Made	Coils Energized	Position of Rotor Reference Pole
A	0-60	1	1 & 1A	0°
B	60-120	1 & 2	1 & 1A 2 & 2A	15°
C	120-180	2	2 & 2A	30°
D	180-240	2 & 3	2 & 2A 3 & 3A	45°
E	240-300	3	3 & 3A	60°
F	300-360	3 & 1	3 & 3A 1 & 1A	75°

Step A. Coils 1 and 1A are energized, and the nearest rotor pole is drawn into alignment.

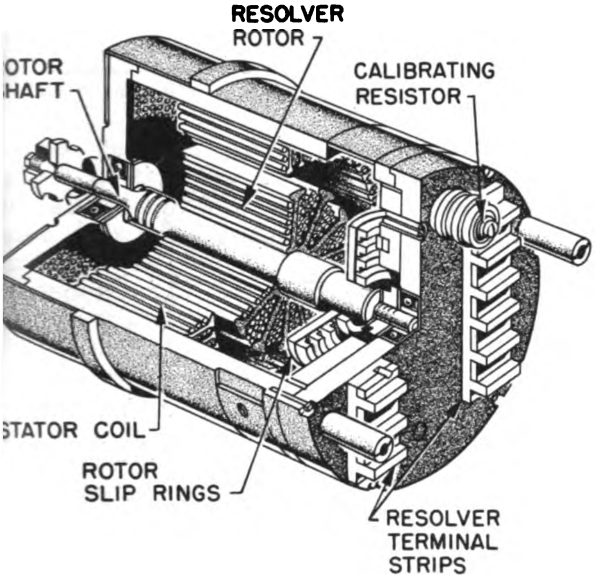
Step B. Coils 1 and 1A and 2 and 2A are energized. There are 90° between rotor poles and only 60° between stator-field poles. Therefore, the rotor, in aligning itself so as to present the path of least reluctance, moves midway between the field coils, or a distance of 15 degrees.

Step C. Coils 2 and 2A are energized. The rotor moves an additional 15° to line up its poles with those of the field coils.

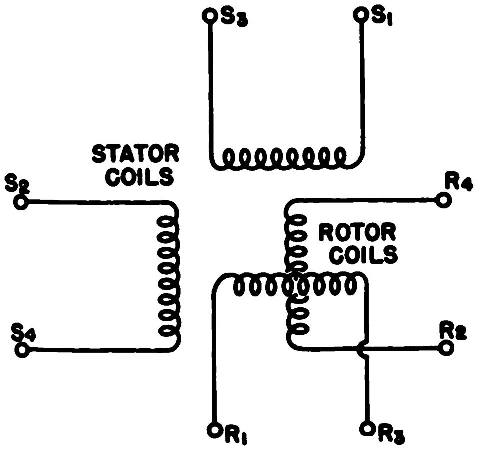
Steps D, E, and F. The rotor moves an additional 15° each step in the manner described above.



166.9
Figure 3-20.—Step-motor action.



12.106
Figure 3-21.—Cutaway of a resolver.



12.105
Figure 3-22.—Resolver schematic.

The output voltage corresponds numerically to e cosine function of the angular displacement tween the rotor and stator. This rotor winding therefore called the cosine winding. With the cond rotor winding displaced 90° from the osine winding, the voltage induced in this winding ould correspond to the sine function of the angle displacement between the rotor and stator. his winding is called the sine winding.

Resolvers are used extensively in computers, coordinate converters, radar sets, weapons direction equipment, target designation equipment, and for data transmission. These devices perform electrical computations involving resolution, composition, and combination. How the resolver performs these computations is explained in the following paragraphs.

The resolver can separate a vector into its two right-angle components; this is called resolution. The hypotenuse of the triangle in figure 3-24 is the vector to be resolved. The angle A represents the direction of the vector; and the voltage applied to the stator winding, given a value of unity, represents the magnitude of the vector. The output voltages E01 and E02, are the answer to the vector problem. The magnitude of E01 represents the horizontal component and E02 the vertical component of the vector.

In figure 3-25 values have been assigned to the inputs. The angle of 30° represents the elevation of a target. The hypotenuse represents the range to the target in the slant plane. In this case unity voltage represents the maximum range of the instrument. The voltage applied to the stator is directly proportional to the target's range. The voltage induced in the cosine winding would represent the horizontal range to the target, while the voltage induced in the sine represents the vertical component of the target's range (height).

Combining the two components of a vector to produce that vector is known as composition. In other words, if the two sides of a right triangle are known and you solve for the hypotenuse, that is composition.

The resolvers use the same formula used in basic mathematics to solve right triangles—

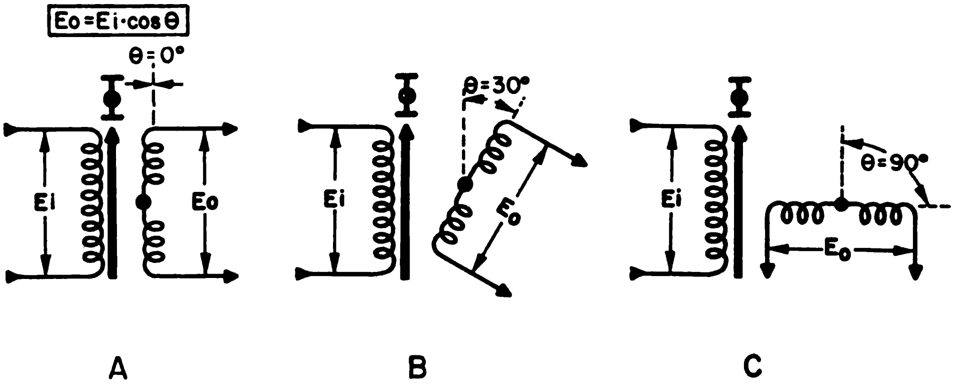
$$a^2 + b^2 = c^2$$

or

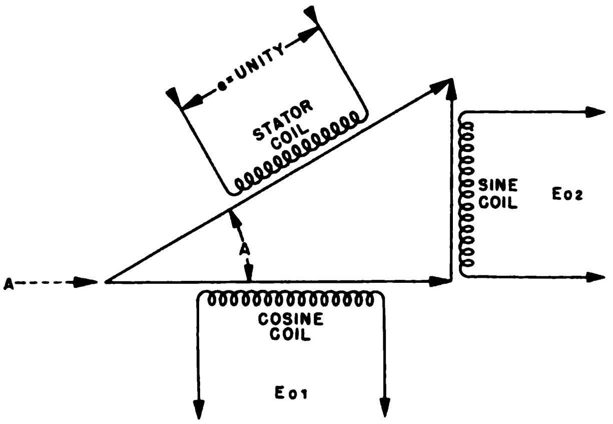
$$\sqrt{a^2 + b^2} = c.$$

Using the problem in figure 3-26 as an example of composition. The two sides of the right triangle are known, with A sin θ and A cos θ representing the voltages of the two sides. The problem is to solve for the hypotenuse A.

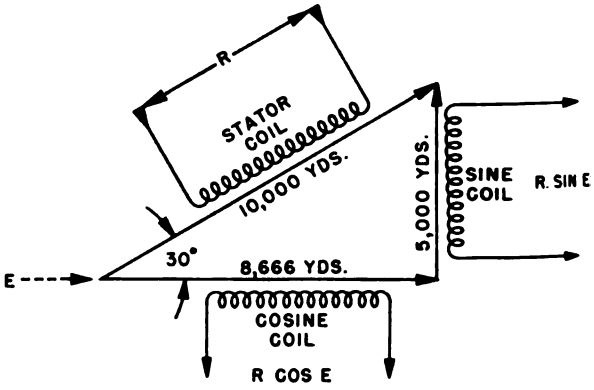
The voltages A sin θ and A cos θ are fed to the two stator coils and each coil produces a flux field proportional to the strength of the voltage unit. These two flux fields are at right angles because the stator coils are at right



12.107
Figure 3-23.—Resolver principle.



12.108
Figure 3-24.—Resolution #1.



12.109
Figure 3-25.—Resolution #2.

angles in the resolver, and right angle flux fields combine according to this formula—

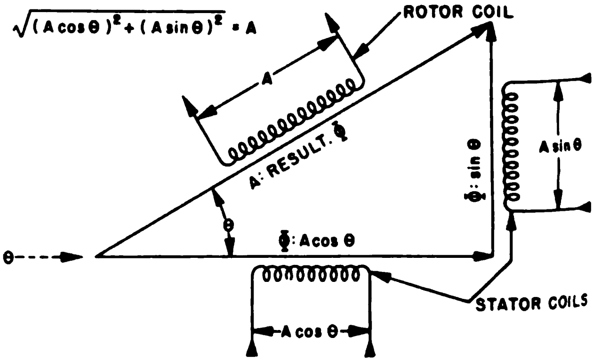
$$\Phi 1^2 + \Phi 2^2 = \Phi t^2$$

or,

$$\sqrt{\Phi 1^2 + \Phi 2^2} = \Phi t.$$

where $\phi 1$ is the field strength of stator coil 1, and $\phi 2$ is the field strength of stator coil 2.

Notice that the resultant flux ϕt is proportional to the square root of the sum of the squares of the two individual fields. Since the



12.110
Figure 3-26.—Composition.

o fields are produced by the voltages $A \sin \theta$ d $A \cos \theta$, the resultant flux is proportional —

$$\sqrt{(A\ \sin\theta)^2 + (A\ \cos\theta)^2}.$$

The resolver rotor is turned through the gle θ so that the axis of the rotor coil comes to alignment with the axis of the resultant ator flux. The voltage induced in the rotor creases as the coupling increases and, at rrespondence, the rotor voltage is propor- onal to the vector A where—

$$A = \sqrt{(A\ \sin\theta)^2 + (A\ \cos\theta)^2}.$$

oltage A is the hypotenuse of the right triangle figure 3-26.

By using two resolvers in a combination rcuit, resolution and composition problems ay be solved simultaneously.

eroing a Resolver

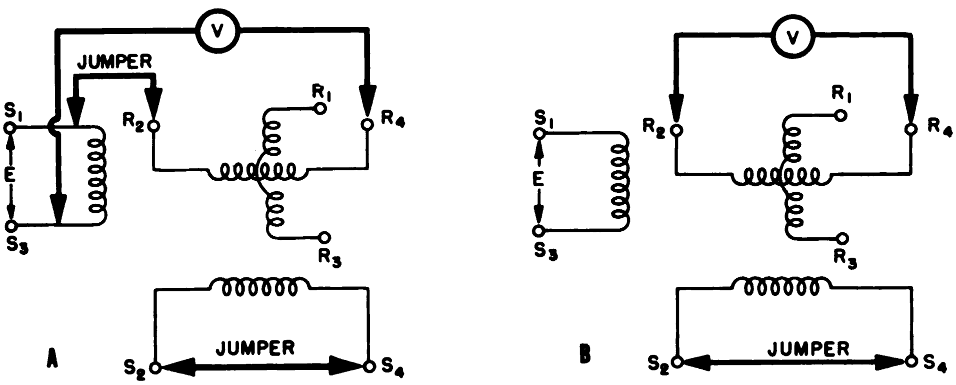
There are many methods used to zero re- olvers. Each manufacturer has his own method. he method described below uses the basic rinciples underlying all the different resolver eroing methods.

Before a resolver can solve a problem it ust have a reference position from which the put values are measured. This is the zero osition of the resolver. The zero position of resolver is determined by the angular rela- ionship between the rotor and stator windings. ach stator winding must be perpendicular to a corresponding rotor winding. When this relationship is established, there will be no magnetic coupling between corresponding windings.

The absence of a magnetic coupling between corresponding rotor and stator windings is possible at two positions 180° apart. To ensure the correct position, so that the phase relationship between the rotor and stator is correct, the coarse zero test is made first. Figure 3-27A shows the connections for the coarse zero test. The voltage applied to the stator winding S1 - S3 is a reference voltage specified for the resolver. The two windings are connected in parallel by the voltmeter and the jumper. The voltmeter will read the applied voltage, plus or minus any voltage induced in the rotor winding. The jumper across the winding S2 - S4 is to eliminate any stray voltage that might originate from the winding.

To make the coarse zero adjustment, loosen the flange mounting screws of the stator. Looking at the rear (brush end), turn the stator counterclockwise. Stop turning when the voltmeter reads the input voltage, E. At this point you know the R2 - R4 coil has no induced voltage becaus the voltmeter reads the input voltage alone. This means that the R2 - R4 is approximately at right angles to S1 - S3 and the rotor is at coarse zero.

With the voltmeter reading the E voltage, turn the stator a little beyond coarse zero. The voltage at the voltmeter should INCREASE ABOVE E, because the voltage induced in the R2 - R4 coils add to E. Be sure the voltage at the voltmeter increases to prevent zeroing at 180° out of phase.



12.111

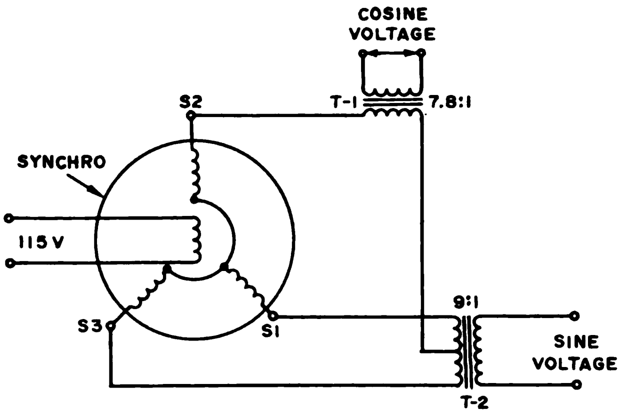
Figure 3-27.—Zeroing a resolver, (A) coarse setting; (B) fine setting.

The next step is to set the resolver on fine zero. Figure 3-27B shows you how to reconnect the jumper and voltmeter. Turn the stator so that the voltage on the voltmeter decreases, and keep shifting the meter to the lower scales until the minimum voltage reading is obtained. The minimum voltage reading means that R2 - R4 is exactly at right angles to S1 - S3, and the rotor is at fine zero. Recheck this voltage after you secure the mounting screws.

Synchro and Scott-T Transformer Resolver

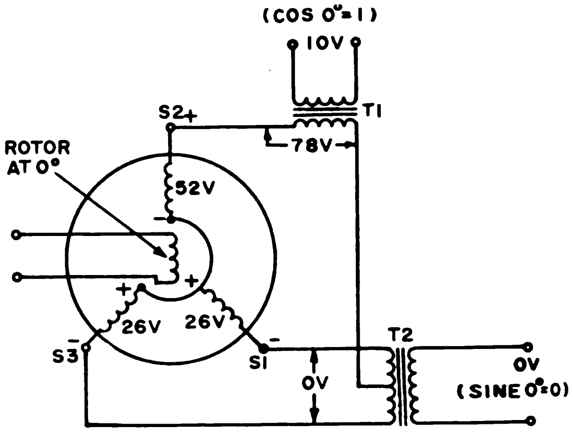
A standard synchro transmitter and Scott-T transformer combination is used in some resolver applications. For example, the cosine transformer T1 (fig. 3-28), has a 7.8-to-1 turns ratio. Its primary winding is connected to the S2 winding of the synchro and the center tap of T2. The sine transformer T2 has a 9-to-1 turns ratio. Its primary is connected to S1 and S3 of the synchro.

Figure 3-29 shows the Scott-T transformer circuit with three angle inputs. In part A of the figure the synchro angle input is zero. The voltages developed by the synchro are +52V at S2, and -26V at S1 and at S3. The potential difference across the primary of T2 is zero. Therefore the output voltage, which is proportional to the sine of the input angle, is zero. There is a 78 V potential difference across the primary of T1, (+58V at S2 and -26V at the center tap of T2). Let's see why there is -26V

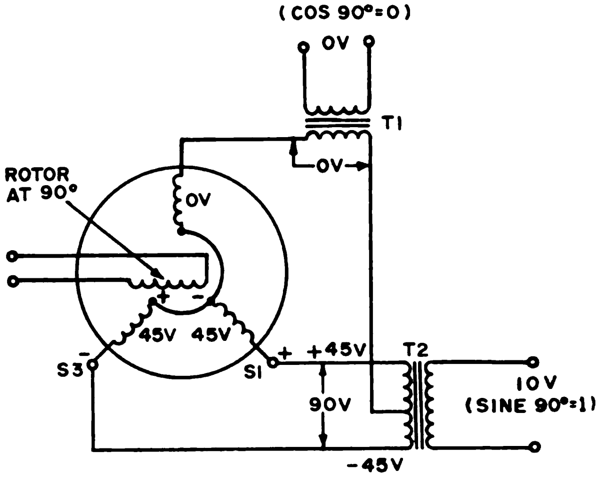


166.39

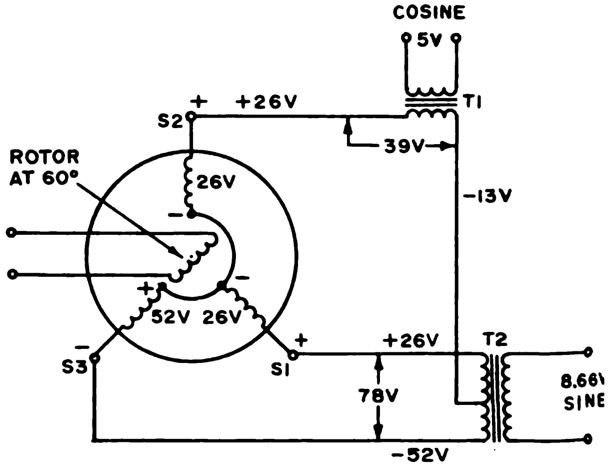
Figure 3-28.—Synchro and Scott-T transformer resolver.



A. ZERO ANGLE



B. 90° ANGLE



C. 60° ANGLE

166.40

Figure 3-29.—Operation of Scott-T transformers.

at the center tap of T2. With no potential difference across T2, there is no current flow between S1 and S3; hence there is a 26V potential throughout the circuit. Current flow from T2 to T1 will be equal and opposite through the two halves of the primary of T2, and therefore will not affect the sine output voltage of T2.

Since there is a 7.8-to-1 stepdown turn ratio in T1, the output voltage across the secondary winding is 10V, which is the maximum output voltage, and is considered to represent unity. Therefore, with the synchro input voltages representing an angle of zero, the Scott-T transformer set outputs are 10V from T1 and 0V from T2.

In part B of figure 3-29 the synchro voltages, +45V at S1, O V at S2, and -45V at S3 represent a 90° angle. There is a 90V potential difference across the primary winding of T2, (+45V and -45V). Since there is a 9-to-1 stepdown turn ratio in T2, the output voltage from the secondary winding is 10V or unity. The potential difference across the primary winding of T1 is zero, and its output is zero. The center tap of T2 is at the midpoint between +45V and -45V, hence it is at zero volts. Therefore, with the synchro voltages representing a 90° angle, the Scott-T transformer set output voltages are OV from T1, and 10V from T2.

In part C of figure 3-29 the synchro voltages, +26V at S1 and S2 and -52V at S3, represent a 60° angle. The potential difference across the primary winding of T2 is 78V, (+26V), and -52V). With the 9-to-1 ratio, the output from T2 is 8.66V. The potential difference across the primary winding of T1 is 39V, (+26V and -13V). With the 7.8-to-1 ratio the output voltage from T1 is 5V. (Since there is 78V across the primary of T2, 39V is dropped across each half of the winding. Hence the potential at the midpoint of the winding is (-52 minus 39 or -13V). Therefore, with the synchro input voltages representing an angle of 60° the output voltages are 8.66V from the sine transformer T2, and 5V from the cosine transformer T1.

If you tabulate the output voltages for the three angle inputs, you will find they are proportional to the sine and cosine functions of the angles. The Scott-T transformer set gives the sine and cosine of other synchro input angles in the same manner as for the angles shown. When the sine or cosine becomes negative, the change in algebraic sign is indicated by a reversal in the phase of the output voltages.

CHAPTER 4

SERVOSYSTEMS

A servosystem (also called servomechanism and servo) is a system that functions to position or control a load in response to an input signal capable of supplying only a very small amount of power. The system operates to reduce to zero any difference that may exist between the actual and the desired position of the load.

Servosystems are used in many applications throughout the Navy. They are used to position loads such as gun turrets, missile launchers, directors, ship rudders, aircraft control surfaces, antennas and searchlights. Depending upon the particular application, servosystems may be either electromechanical, electrohydraulic, hydraulic, or pneumatic. The electromechanical type is by far the most widely used, with the electrohydraulic being next. Pneumatic servos are seldom used in Navy applications.

This chapter describes the basic open and closed loop servosystems and then presents a discussion on the various types of error detectors, servoamplifiers, and associated circuitry used in servosystems. Also discussed are some of the errors inherent in servosystems and the methods by which these errors are reduced or compensated for.

BASIC SERVOSYSTEMS

The major components of a servosystem are the error detector, servoamplifier, and error reducer as shown in figure 4-1. The error detector (in an electromechanical servosystem) may be a potentiometer, synchro control transformer, or other electrical devices which function to provide an output signal corresponding to the magnitude and direction of the input. The amplifier may be any one or combination of, various types of electron tube, transistor, or magnetic servoamplifiers. The error reducer (sometimes referred to as the prime mover) is usually an a.c. or d.c. servomotor as discussed in chapter 1.

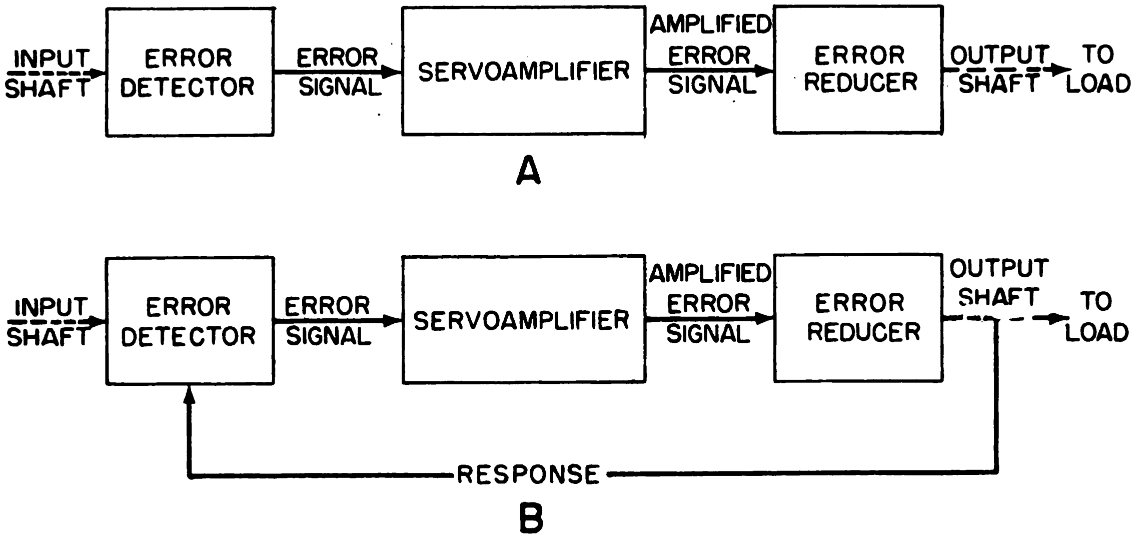
In the basic system (fig. 4-1A), any movement of the input shaft will generate an error signal output from the error detector. This error detector output signal will have a magnitude proportional to the amount of movement of the input shaft, with the phase or polarity of the signal dependent upon the direction the input shaft is moved. The error signal, after amplification, supplies the error reducer which then moves the output shaft or load in the proper direction so as to correspond with the input shaft. The error reducer will not stop driving the output shaft, however, until the input shaft is returned to the original position resulting in a no-signal output from the error detector. This type of servosystem is called an OPEN LOOP system and generally requires an operator who controls the speed and direction of movement of the output by varying the input.

Open loop servosystems are used in manually operated machine tool drives and other industrial and military applications.

The CLOSED LOOP system (fig. 4-1B), however, is more widely used.

Note in figure 4-1B a response line from the servo output to the error detector has been added. This makes the error detector responsive to the servo output and functions to cause the error detector output signal to be zero when the input and output shafts are in correspondence. The error detector in a CLOSED LOOP servosystem compares the input signal representing the order or command to the output signal representing the position of the load, and provides an error signal output proportional to the difference between these two signals.

The response in a closed loop servosystem may be either mechanical or electrical, depending upon the design of the system. In mechanical response, the error reducer in driving the load to its ordered position also, at the same time, drives (usually through gearing) the error detector to its null or no-signal position. In electrical response, the error reducer, while posi-



175.23

Figure 4-1.—Basic servosystems: (A) Open loop; (B) Closed loop.

ioning the load, generates an electrical voltage hich opposes the error detector output. In both ases, the system functions automatically to keep he input and output shafts in correspondence.

The servo shown in figure 4-1B is called a OSITION servo. It is used to position an infinite umber of devices, such as valves, control urfaces, platforms, etc. Another type of closed oop servo, called a VELOCITY servo is shown n figure 4-2.

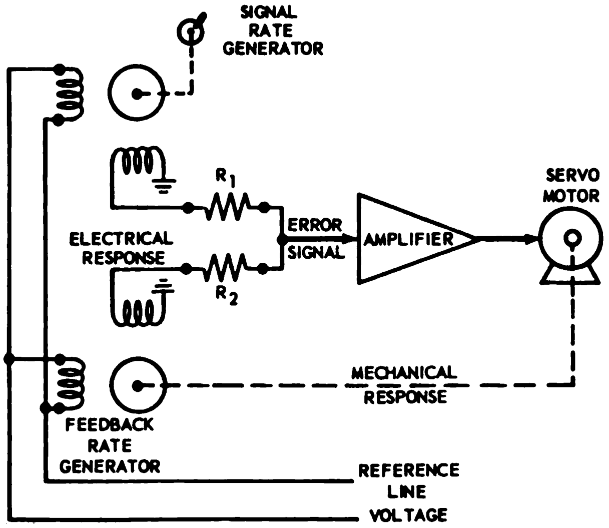
In velocity servos the input signal is proportional to a rate. The velocity of the output s the primary function of this type of control. Position is a second order function, being derived from the velocity and time. (In position servos velocity is a second order function which s derived from position, the primary function, and time.) Hence a velocity servo's primary function is the opposite of that of a position servo. The basic functional elements of the two types are identical; each has an error detector, an amplifier, and an error reducer. In position servos the error signal represents a displacement, and is eliminated by reducing the displacement. In velocity servos the error signal voltage is proportional to a velocity, and is eliminated by a response voltage proportional to the output velocity.

The rate generators in figure 4-2 develop a voltage proportional to the velocity of their rotors, as explained in chapter 1.

The output voltage from the signal rate generator is the input to the amplifier via resistor R1 (fig. 4-2). The magnitude of the signal is proportional to the velocity of the rotor, which we will turn with the handcrank. The phase of the signal is determined by the direction in which the rotor is turned. The signal is amplified, and drives the servomotor. The motor drives the load and the response rate generator. The output of this generator is fed back to the input circuit of the amplifier via R2. The response voltage is 180° out of phase from the input signal voltage. The servo's error detector is the summing network consisting of the resistors R1 and R2. When the magnitude of the response voltage is equal to the input signal voltage, the two will be in balance and the error voltage will be zero. This will occur when the servo's output velocity is equal to the desired velocity.

Note that the position of the output is not considered in the explanation. Position is a function of velocity and time in this type of servo. Acceleration is a change in velocity. Hence if we changed the speed or direction of rotation of the handcrank in the diagram, the change in the generator's output would be proportional to an acceleration signal.

The velocity servo is used in applications where the controlled output variable drives a load device at a constant speed, which is established by the level of the error signal present. The types of load it might drive include radar



12.287
Figure 4-2.—Velocity servo.

antennas, shafts, star tracking telescopes, machine cutting tools or any device requiring variable speed regulation.

ERROR DETECTORS

Most error detectors used with electrical servosystems are of either the potentiometer (resistive) type, or one of several types of magnetic devices.

Electrical error detectors may be either a.c. or d.c. devices depending upon the requirements of the servosystem. An a.c. device used as an error detector must compare the two signals and produce an error signal of which the phase and amplitude will indicate both direction and amount of control necessary for correspondence. A d.c. device differs in that the polarity of output error signal determines direction of the correction necessary.

POTENTIOMETERS

Potentiometer error detectors are generally used only where the input and output of the servomechanism has limited motion. They are characterized by high accuracy, small size, and the fact that a d.c. or a.c. voltage may be obtained as the output. Their disadvantages include limited motion, a life problem resulting from the wear of the brush on the potentiometer wire, and the fact that the voltage output of the potentiometer changes in discrete steps as the brush moves from wire to wire. A further disadvantage of some potentiometers is the high drive torque required to rotate the wiper contact.

A potentiometer is one of the simplest means of converting mechanical positional information to a proportional voltage, or vice versa.

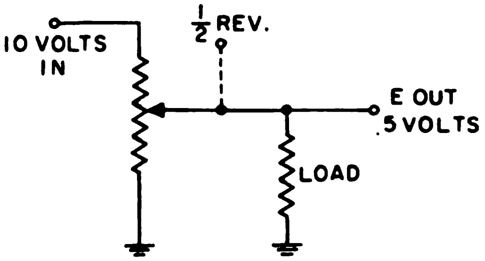
Basically, a potentiometer solves a percentage problem. The electrical input, which may be either an a.c. or a d.c. voltage, is applied across the winding of the potentiometer (fig. 4-3). Unity in the percentage problem is represented by the instantaneous value of the input voltage and by the total resistance of the winding.

The wiper arm or sliding contact is moved by the mechanical input along the winding to "pick up" a percentage of the input voltage. In the diagram the wiper is positioned half-way down the potentiometer winding, the input voltage is 10 volts; the output from the wiper is 5 volts, or 50% of the input voltage and of the total resistance of the winding.

A potentiometer is a variable voltage divider, with an output voltage that is a percentage of the input voltage. The amount of output voltage is proportional to the position of the wiper. The resistance from one end of the winding to the wiper is in series with the load while the remainder of the resistance is in parallel with the load. Thus a potentiometer is a voltage control device.

Potentiometer Construction

Most of the potentiometers used as error detectors are wire wound. The resistance wire is wound around a form called a card or mandrel. The wiper arm glides along the resistance wire making contact with it to complete the output



166.4
Figure 4-3.—Problem solved by a potentiometer.

ircuit. The movement of the wiper from one turn o the next will add resistance between the wiper nd one end of the winding, while simultaneously emoving an equal amount of resistance from etween the other end and the wiper. Since the oltage drops along the winding are proportional o the resistance, the voltage picked off by the iper increases from zero at one end of the inding to maximum value at the other end.

In most of the potentiometers the motion of he wiper arm is rotary and the card has a ylindrical shape (fig. 4-4). There are singleurn potentiometers, in which the wiper is limited o one revolution or less, and multiturn potentiometers, in which the wiper can make many evolutions.

The wiper arm in some potentiometers moves n a translatory manner (back and forth in linear motion). This type has limited application, however, its operation is the same as potentiometers with rotary wiper motion.

Types of Potentiometers

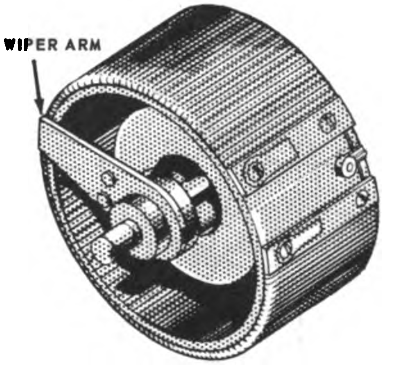
LINEAR POTENTIOMETERS.—A linear potentiometer's resistance wire is evenly wound and its card is of uniform width throughout. Thus the input voltage is distributed equally across each turn of the resistance wire and evenly along the winding. Therefore, a movement of the wiper from one turn to the next will add equal amounts of resistance. And it follows that the output voltage will vary linearly with the movement of the input shaft. In other words, for the same amount of shaft rotation equal changes in the output voltage will be obtained.

NONLINEAR POTENTIOMETERS.—A nonlinear potentiometer is one whose voltage output is proportional to a nonlinear function of the input shaft's rotation. The resistance wire is wound on specially shaped cards so that each turn has a different length of wire. Thus, the total resistance is distributed unevenly along the length of the winding. Therefore, the voltage output will vary in a nonlinear fashion as the wiper is moved from one turn to another.

Balanced Potentiometer

A basic closed loop servosystem using a balanced potentiometer as an error detector is shown in figure 4-5.

The command input shaft is mechanically linked to R1, and the load is mechanically linked to R2. An electrical supply voltage is applied across both potentiometers.



33.75
Figure 4-4.—Wire wound potentiometer.

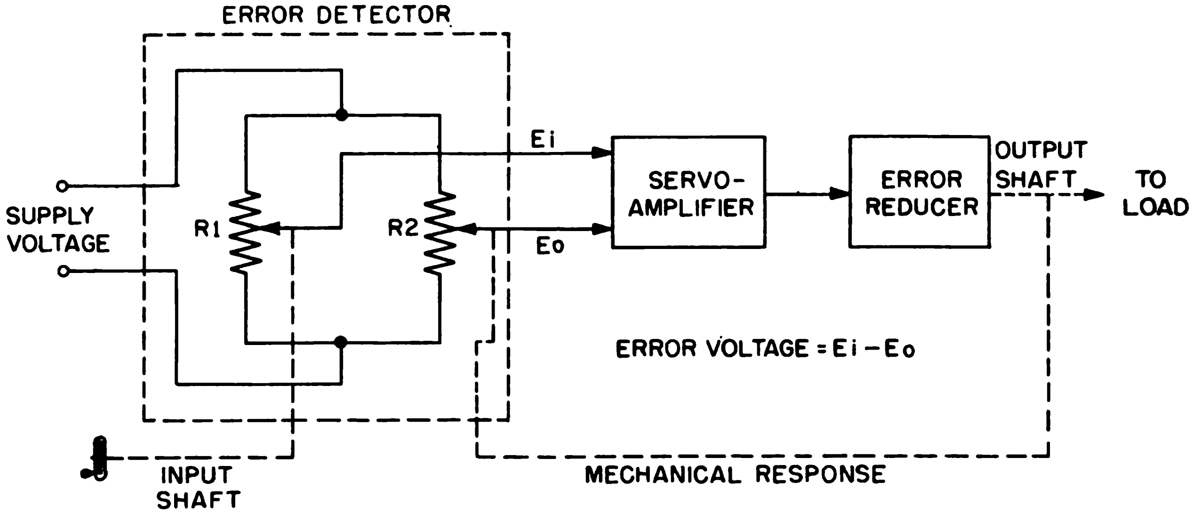
When the input and output shafts are in the same angular position, they are in correspondence and there will be no output error voltage. If the input shaft is rotated, moving the wiper contact of R1, an error voltage will be applied to the servoamplifier. This error voltage is the difference of the voltages at the wiper contacts of R1 and R2. The output of the amplifier will cause the motor to rotate the load and the wiper contact of R2 until both voltages are equal; thus, there is no output error voltage.

Figure 4-5 illustrates R1 and R2 grouped together. In actual practice the potentiometers may be positioned remotely from each other, with R2, the output potentiometer, being located at the output shaft or load. This remote location of one of the components does not remove it from being a part of the error detector.

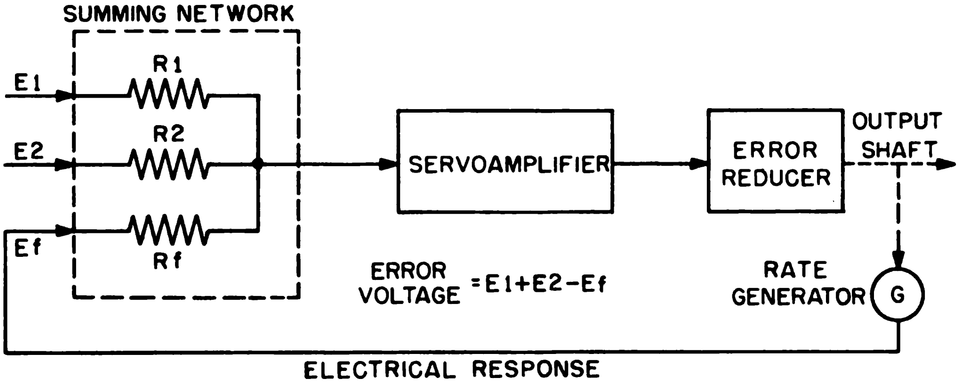
SUMMING NETWORKS

Summing networks (fig. 4-6) are used as error detectors in servo applications where the servo output must be proportional to the algebraic sum of two or more inputs. As in the case of potentiometers, the networks may be either a.c. or d.c. with the phase or polarity of the input voltage determining whether the signals are additive or subtractive.

If two input signals E1 and E2 (fig. 4-6) are applied to the network, the network will provide an error voltage output proportional to the algebraic sum of the two signals. The servomotor, in driving the load also drives a rate



175.24
Figure 4-5.—Balanced potentiometer as an error detector.



175.25
Figure 4-6.—Summing network as an error detector.

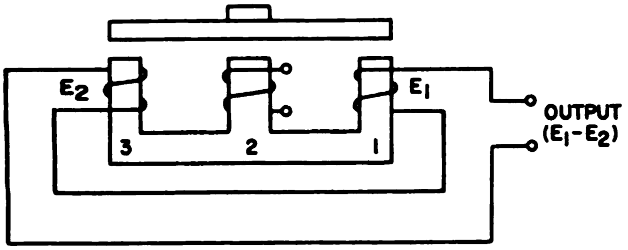
generator which supplies the voltage to feedback resistor Rf to null the error signal.

In some installations the servomotor may position the wiper arm of a potentiometer instead of driving a rate generator to supply the feedback voltage.

E-TRANSFORMERS

A type of magnetic unit which is used as an error detector is the E-transformer. Its application is useful in systems that do not require the error detector to move through large angles. In the basic E-transformer an a.c. voltage is applied to the primary coil (2 fig. 4-7) located on the center leg of the laminated E-shaped core. Two secondary coils (1 and 3) are wound in series opposite on the outer poles of the structure. The magnetic coupling between the primary (coil 2) and the two secondaries varies with the position of the armature. The armature can be displaced laterally in either direction in the magnetic circuit. This changes the reluctance between either pole and the armature.

When the armature is located in the center of the structure, as shown in the figure, equal voltages are induced in the secondary coils, and



55.19
Figure 4-7.—Basic E-type transformer.

the difference between them is zero. Thus, the voltage at the output terminals is also zero.

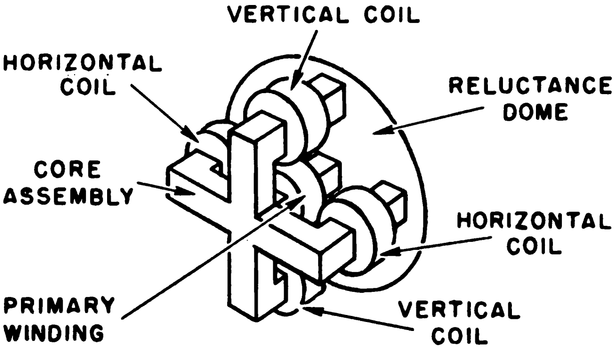
But if the armature is moved, say, to the right, the voltage induced in coil 1 increases, while the voltage induced in coil 3 decreases. The two voltages are then unequal, so that the difference is no longer zero, and a net voltage results at the output terminals. A sense of direction is provided since the output voltage changes phase as the armature passes through the null (center position). The output voltage phase will be either in phase with the primary voltage or 180° out of phase. The amplitude of the output voltage is proportional to the amount the armature moves back and forth from the center position.

The basic E-transformer (fig. 4-7) will detect movement of the armature about only one axis (either the horizontal or vertical depending upon the way the unit is mounted). To detect movement about both the horizontal and vertical axes, a crossed-E transformer is used.

If you place two E-transformers at right angles to each other and replace the bar armature with a dome-shaped one (fig. 4-8) you have the basic configuration of what is known as the crossed-E transformer, or pickoff. In most applications the dome-shaped armature is attached to a gyro, and the core assembly is fixed to a gimbal which is the servo load.

The crossed-E transformer assembly consists of five legs (poles). Each leg is encased by a coil. The coil around the center leg is the primary, which is excited by an alternating voltage. The remaining four coils are the secondaries. Figure 4-9A shows a cross-sectional view of the crossed-E transformer and the flux paths through the armature. Part B of figure 4-9 shows how the crossed-E transformer looks from the front. From this view you can see how it gets the name, crossed-E.

When the reluctance dome is to the left of center, more flux links the left leg with the primary coil and the voltage induced in the left secondary increases. The right leg has fewer flux linkages with the center coil; therefore, the voltage induced in the right coil will be less than that in the left coil. Thus there will now be a net voltage out of the pickoff. The phase of the output will be that of the larger voltage. It follows that if the dome is moved to the right, the opposite condition would exist. From this brief description, you can see that the crossed-E transformer works on the same fundamental principle as the basic type described earlier. The major difference between the two is in shape and the number of secondaries, and in the fact that the armature has universal movement.

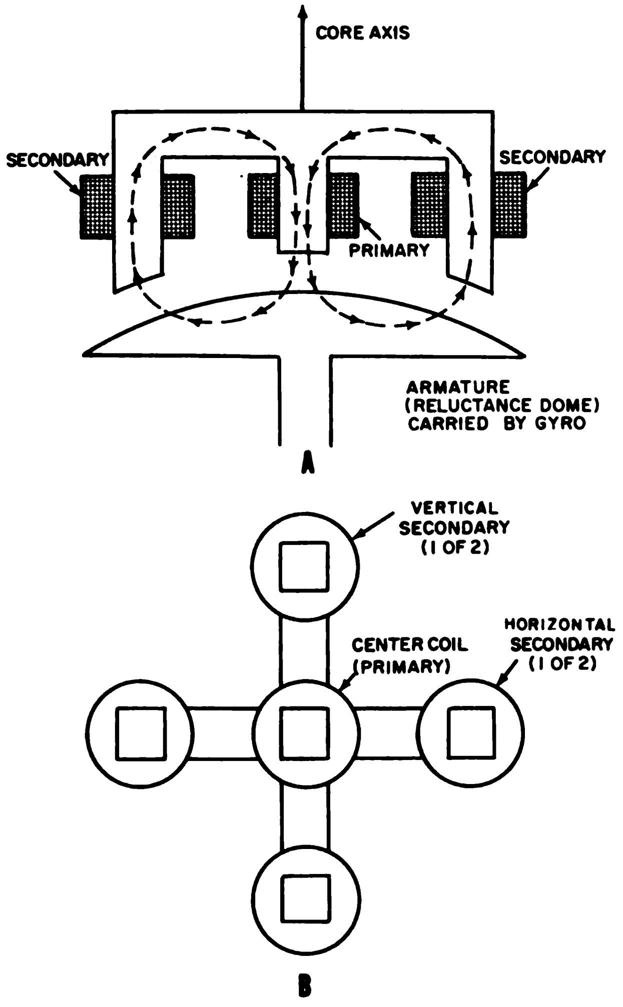


55.23
Figure 4-8.—Crossed-E transformer showing location of components.

CONTROL TRANSFORMERS

A commonly used magnetic error detector is the synchro control transformer which is used in conjunction with a synchro data transmission system. A primary advantage of the CT over other types of error detectors is its unlimited rotation angle; that is, both the input and the output to the synchro control transformer may rotate through unlimited angles. One of the disadvantages is the fact that the output supplied to the servo amplifier is always a.c. modulated with the servo error, and must be demodulated if it is to be applied to a d.c. servomotor.

The synchro data transmission system comprises a synchro transmitter, a synchro control transformer, and in some cases a differential transmitter for additional servo inputs. The synchro transmitter transforms the motion of its shaft into electrical signals suitable for


CORE AXIS
SECONDARY
SECONDARY
PRIMARY
ARMATURE (RELUCTANCE DOME) CARRIED BY GYRO
A
VERTICAL SECONDARY (1 OF 2)
HORIZONTAL SECONDARY (1 OF 2)
CENTER COIL (PRIMARY)
B

55.21A

Figure 4-9.—Crossed-E transformer: (A) Cross section; (B) Front view.

transmission to the CT which functions as the error detector.

A servo using a CT as an error detector is shown in figure 4-10. The CX provides the input signal to the CT. The CT, in turn, compares the input (order) signal with the actual position of the load and provides an error signal output from its rotor to the servoamplifier. The servoamplifier output supplies the control field of an a.c. servomotor (of the type discussed in chapter 1) with voltage of the proper phase so as to cause the motor to drive the load into correspondence with the input. In driving the load, the servomotor also drives the CT rotor (through gearing) to its null position.

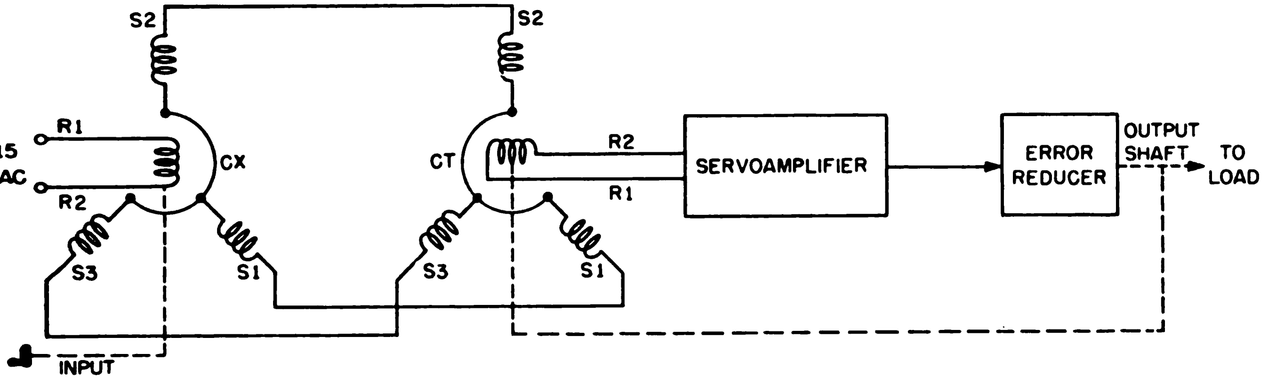
In cases where a synchro differential transmitter is used for an additional input to the servosystem, it is connected between the synchro transmitter and the CT as shown in figure 4-11. When the synchro differential rotor is in line with its stator windings, the differential transmitter acts as a one-to-one ratio transformer and the voltages applied to the CT are the same as the voltages from the synchro transmitter. If the synchro differential transmitter rotor is displaced by a second input, the voltages from the synchro transmitter to the CT will be modified by the synchro differential transmitter by the amount and direction of its rotor displacement. Thus, the two inputs are algebraically added and fed to the CT as a single input.

As stated in chapter 2, control transformers are sometimes designed with rotatable stators. A CT of this type is sometimes used as an error detector in servos having two inputs. The second input rotates the CT stator instead of a differential transmitter as in figure 4-11.

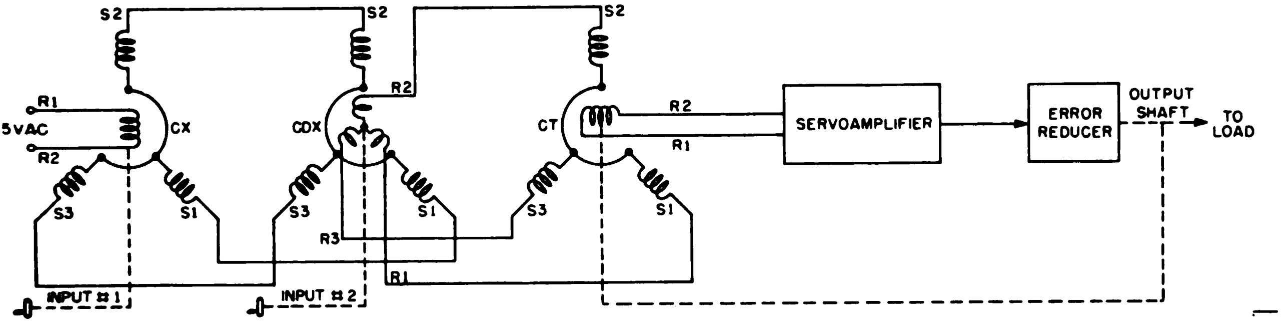
Synchronizing Networks

As stated in a previous chapter, dual-speed servosystems use two CTs (one coarse and one fine) as error detectors. The output from the coarse CT supplies the error signal when the system is far out of correspondence with control being shifted to the fine CT when the system is within two or three degrees of synchronization. A synchronizing network (also called a crossover or switching network) senses how far the servo load is from the ordered position and then functions to switch the appropriate signal into control. The signal selected by the circuit is the input to the amplifier. The selection is based on the size of the error signals the circuit receives. The coarse signal is the predominant factor in the selection, since it is a measure of the servo's output position throughout its limit of motion. The coarse signal drives the system into approximate synchronization, where the fine signal is shifted into control.

RELAY-OPERATED SYNCHRONIZING NETWORK.—The relay circuit (fig. 4-12) connects the fine or the coarse CT to the amplifier. One side of the error signals is connected to the fixed contacts of relay K1. The other side of the error signals is grounded and thus is common. The movable contact of K1 is spring loaded so that it makes connection with the fine signal



175.26
Figure 4-10.—The CT as an error detector.



175.27
Figure 4-11.—The CDX as an additional input.

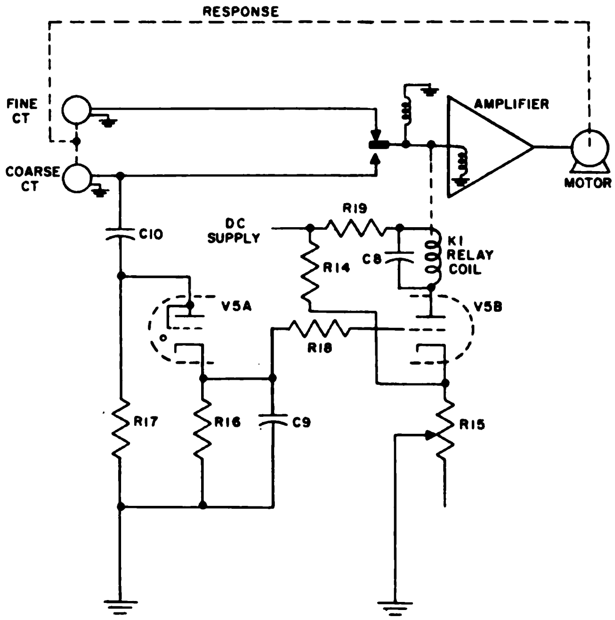
contact. Therefore, when K1 is deenergized the fine signal is passed to the amplifier, and conversely when K1 is energized the coarse signal has control. Hence, the coarse signal is used to control the d.c. supply to the coil of K1.

The coarse signal is applied to the plate of V5A. The plate and grid of V5A are tied together and the tube operates as a diode, half-wave rectifier. When the plate is positive, it will conduct. The output from V5A is a pulsating d.c. voltage taken from the top of R16, the cathode resistor. Thus V5A rectifies the coarse signal.

Tube V5B is in series with the coil of K1. V5B is biased below cutoff by the cathode resistor, R15. The grid potential varies with magnitude of the rectified coarse signal from V5A. If the gird signal exceeds a fixed value, V5B will conduct. When this occurs current flows in the plate circuit and energizes K1. The relay will pick up and shift control to the coarse error signal.

The circuit for K1 is from ground through R15 and V5B, then through the coil of K1 and R19 to the positive side of the line. Since the signal to the grid of V5B is a pulsating d.c. voltage, the tube's conduction will pulsate which will cause the relay to chatter. C8 is placed across the coil of K1 to reduce the chatter of the relay. R19 is a voltage-dropping resistor in series with the relay coil. R14 and R15 form a voltage divider circuit. R15 is adjustable and controls the cathode bias of V5A.

R15 is adjusted so that V5B will conduct and K1 will pick up when the size of the coarse error signal is the proper value. Normally this will occur when the servo is from two to three degrees out of synchronism. The exact value of error signal will depend on the characteristics of the servo. Generally speaking, we want the



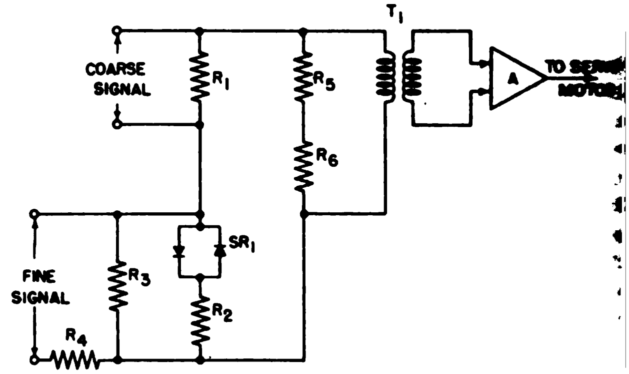
166.19
Figure 4-12.—Relay synchronizing network.

fine CT in control of the servo as long as possible. For a small displacement the fine error signal is much larger and provides a much tighter control of the servo. But if too large a coarse error signal is needed to pick up K1, we risk the possibility of a false synchronization or the servo oscillating about the synchronization point as the fine and coarse CTs buck each other.

SELENIUM DIODE SYNCHRONIZING NETWORK.—Figure 4-13 shows a synchronizing network which uses selenium diodes (rectifiers) to perform the signal switching function. Notice that there is no contact switching arrangement. This means that both fine and coarse signals are always connected to the amplifier. It also indicates that the fine signal must be shunted away from the amplifier when a large error is present.

The coarse signal is introduced across R1, and the fine signal across SR1, R2 and R4. Notice that R1, SR1 and R2 form a parallel circuit with R5 and R6. The amplifier's input signal (from T1) is developed across R5 and R6.

First, study the circuit as it handles a small error. The fine synchro is displaced much more than the coarse synchro. This makes the fine signal much stronger than the coarse signal. Both signals appear across R5 and R6. However, the fine signal overrides the coarse signal and is the input to the amplifier. Thus when the error is small, the fine signal has control.



55.30.0
Figure 4-13.—Selenium diode synchronizing network.

Now study the circuit as it handles a large error. You know that the fine signal must be shunted so that the coarse signal can take control. The selenium rectifier, SR1, does the job of shunting the fine signal. When the error is large with respect to the desired position and the load position of the servo, both the coarse and fine synchro signal voltages are large. The fine signal across SR1 exceeds its forward breakdown voltage and its resistance falls to a very low value. Most of the fine signal voltage is dropped across the series resistor, R4, with practically no voltage developed across R2 and the diodes.

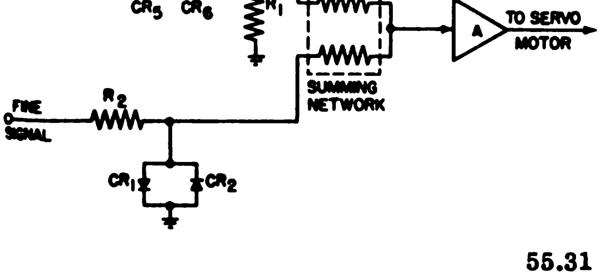
The selenium diodes are the tricky part of the circuit. For a small error, the signal voltage is comparatively weak and SR1 conducts proportionately. As the signal increases, the current flow across SR1 increases until it reaches a point where the diode's resistance breaks down under the load. At this point, the voltage developed across SR1 and R2 drops to a very low value. This puts practically all the fine signal across R4. Effectively, the fine signal is shunted from the parallel circuit of R5 and R6. The coarse signal becomes the input to the amplifier.

As long as a relatively large current passes through SR1, it will remain in its shorted condition. When the current across it decreases, however, the selenium rectifiers resistances will return to their previous high value, at which time the fine signal will resume control.

The semiconductor diode synchronizing network is fairly common, so let's take a look at another circuit using this technique. This circuit is illustrated in figure 4-14. Within a range of approximately 3° on either side of the synchronizing point, the coarse signal is effectively blocked because of the high impedance of the series diodes, CR3, CR4, CR5, and CR6. With the coarse signal blocked, the fine signal is fed into the summing network and is in control of the servo. However, this signal is limited to a very low voltage by the parallel diodes, CR1 and CR2.

Both the fine and coarse voltage inputs will increase as the error in correspondence is increased. Remember that the resistance of the diode rectifier decreased with an increase in current flow across it. CR1 and CR2 develop the fine signal. A point will be reached (about 3° error) when CR1 and CR2 will be incapable of dropping a greater voltage. Any increase in current gives us a decrease in resistance and a decrease in the fine voltage output to the summing network.

Now let us look at the coarse signal. In figure 4-14 you will notice that the coarse signal is developed across R1. Also notice that the diode network of CR3, CR4, CR5, and CR6 is in series with R1. Errors in correspondence which are less than 3° will cause some current to flow across R1 and the diode network. However, this current is small and will cause the diode network's resistance to be high. Therefore most of the coarse signal voltage is dropped across the diode network and very little voltage is developed by R1. In this condition the resultant voltage in the summing network is predominantly from the fine synchro. As we get further out of synchro correspondence, the current through the coarse signal diode will increase causing a decrease in the diode network's resistance. A smaller percentage of voltage will be dropped across the diode network and thus more signal voltage developed across R1. Circuit resistance is selected so that the voltage developed across R1 (coarse signal) will override the voltage across CR1 and CR2 (fine signal) when the synchro correspondence error is 3° or more. The coarse signal now has control of the servo. When the servo error becomes less than 3°, the fine signal resumes control.



55.31

Figure 4-14.—Semiconductor diode synchronizing network.

In similar circuits, zener diodes are used in place of the selenium or crystal rectifiers.

Stickoff Voltage

A servosystem will stop driving when the error signal is zero. A CT, however, has two positions 180° apart where its output is zero. Thus a servosystem controlled by a CT can synchronize at either position. This is possible in a dual-speed synchro system with an even speed ratio. Since both receivers are zeroed together both would be at the true correspondence and the false correspondence positions together. Hence a servosystem could not distinguish between the two positions. In applications where remote and often unattended servosystems are used, the possibility that a false synchronization could occur must be eliminated.

No CT is perfect, and each has an inherent dead space. The fine CT however, has little or no dead space to speak of. Therefore the slightest change in the signal or movement of the servosystem's response will bring the fine CT out of its dead space. Once out of its dead space the fine CT will cause the servosystem to drive. You might think then that we do not have a false synchronization problem. But suppose that when the system is energized the transmitters and receivers are close to being 180° apart. The coarse signal would be too weak to assume control of the system, and the fine CT would have control. Therefore, the servosystem would drive until the fine signal is zero and remain there. The servosystem could not sense the difference between 180° and zero synchronization.

In order to make all positions distinguishable, a "stickoff" voltage (sometimes called antistickoff), is applied to the coarse signal. In figure 4-15A the secondary winding of the stick-

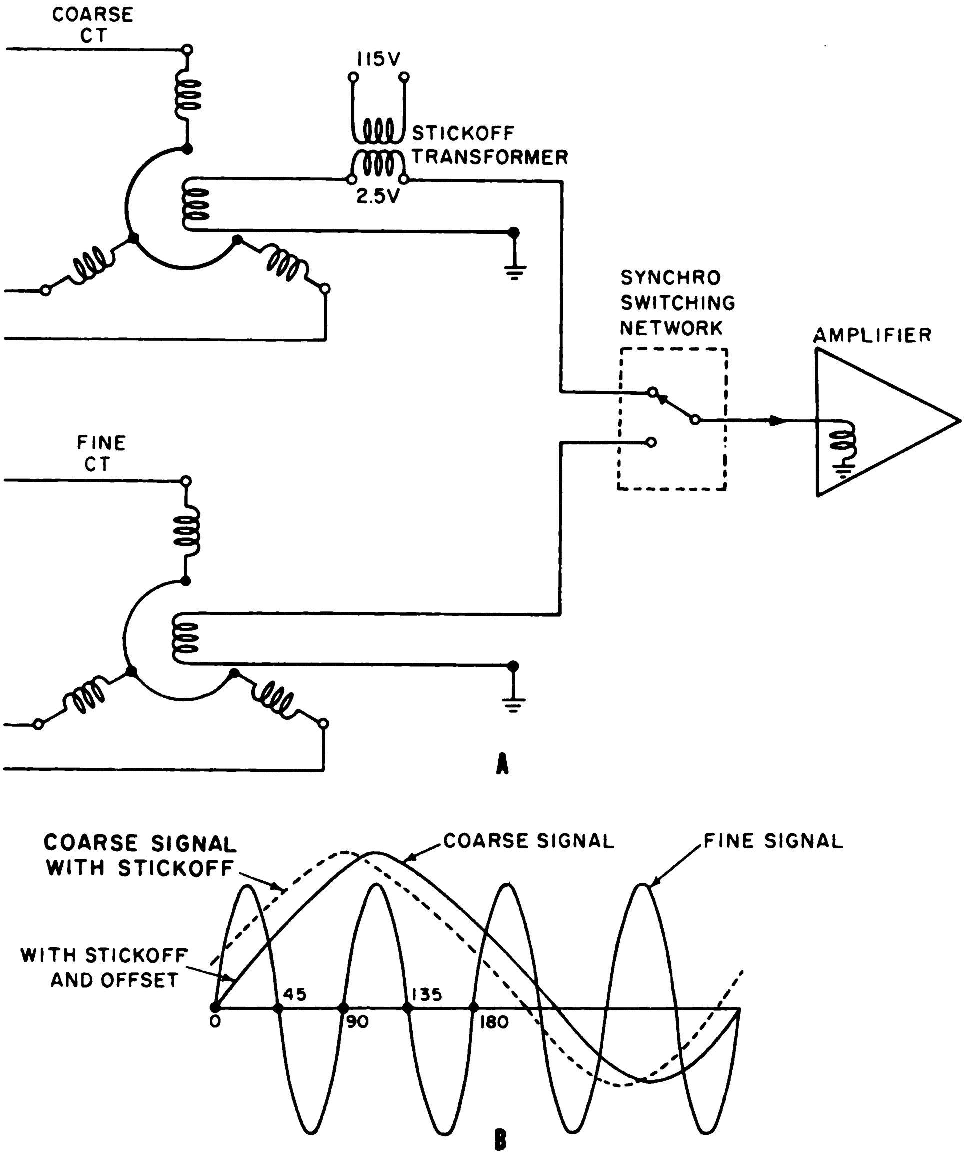


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Figure 4-15.—Stickoff voltage in coarse signal circuit.

off transformer is shown in series with the coarse CT output. The voltage induced in the secondary of the transformer in effect shifts the electrical zero position of the coarse CT. The coarse CT is rezeroed and is offset from the fine CT by an amount equivalent to the stickoff voltage. This makes the coarse and fine CT put out zero volts at zero degrees but not at 180°, (fig. 4-15B). Now, the two positions are distinguishable to the servosystem.

SERVOAMPLIFIERS

In addition to amplifying the error signal sufficiently to drive the servomotor, servoamplifiers must, in some cases, convert the error signal from a.c. to d.c. or vice versa. They may also include provisions to obtain stable, fast, and accurate system operation. Both a.c. and d.c. amplifiers are used as servoamplifiers, however, the a.c. amplifier is more ommon because of the problems associated vith d.c. amplifiers. These problems include lrift, (a variation in output voltage with no hange in input) and the necessity for special ias voltages in cascaded stages.

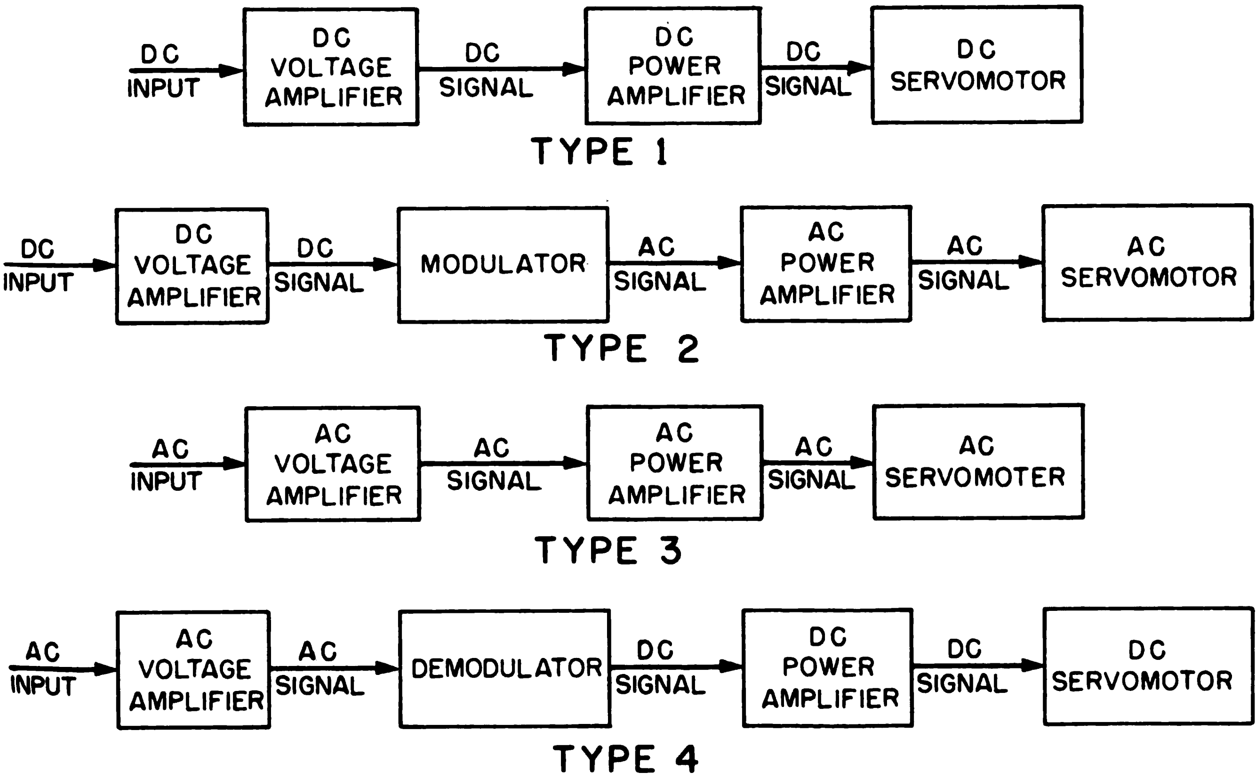
Desirable characteristics in servoamplifiers nclude a flat gain versus frequency response or a frequency well beyond the frequency range ised, a minimum of phase shift with a change n input signal, a low output impedance, and a ow noise level.

As the servosystem is a null seeking system, inearity is not nearly as important in servoamplifiers as in audioamplifiers. Also, the servomotor or other type of error reducer driven by the servoamplifier can withstand a much higher level of distortion than the human ear. Thus, servoamplifiers are often driven far beyond the limit of distortionless output.

Servoamplifiers generally have a voltage amplifier or preamplifier stage followed by a power amplifier stage. The voltage amplifier amplifies the error signal without changing its electrical characteristics and the output of the power amplifier supplies the servomotor. The amplifier may also include a modulator to convert a d.c. signal into an equivalent a.c. signal or a demodulator to convert an a.c. signal into an equivalent d.c. signal. Servoamplifiers may be classified as to their input and output into four basic types as shown in figure 4-16.

MODULATORS

As shown in figure 4-16, some servos have a d.c. error voltage and an a.c. amplifier or motor. Consequently, the d.c. error voltage must be converted to an a.c. voltage that contains the same data (the direction and magnitude of the error) before it can be used. The circuit that converts the signal from d.c. to an a.c. voltage is called a modulator. Modulation is the process by which the amplitude, frequency, or phase of a carrier wave is varied with time in accordance with the wave form of a



175.28

Figure 4-16.—Basic types of servoamplifiers.

superimposed intelligence. Modulation and demodulation are covered in Basic Electronics, NavPers 10087-(rev.)

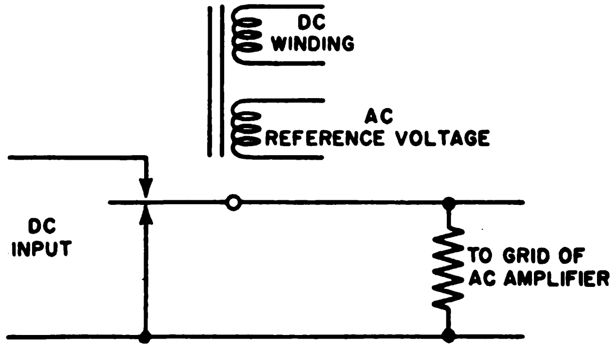
In the modulator circuit the carrier wave is the servo's a.c. reference voltage. The superimposed intelligence is the d.c. error signal. The polarity of the d.c. error voltage indicates the direction of the error, and its magnitude is proportional to the amount of error. Therefore, the phase of the a.c. signal, and the magnitude of the a.c. signal is proportional to the d.c. signal voltage.

The modulator circuits use elements that act as synchronous switches. Examples of these elements are: transistors, crystal or metallic rectifiers, diodes, triodes, and mechanical contactors. The elements have a nonlinear front-to-back resistance ratio, so that current will flow through the "switch" in one direction. The switches are operated at the carrier frequency which is usually 60 or 400 hertz. The resulting pulsating voltage is proportional to the d.c. error voltage. The phase of the pulsation voltage is determined by the polarity of the d.c. error signal.

Vibrator Modulators

A modulator may be either an electromechanical or an electronic circuit. An example of an electromechanical circuit, called a vibrator or chopper, is shown in figure 4-17. The coil is energized by alternating current at the appropriate frequency, usually 60 or 400 hertz.

To prevent the vibrating arm from being attracted twice by the coil during each cycle, some direct current is passed through the coil, or through another coil wound on the same core. Thus when the alternating current flows in the other direction, its magnetizing force is canceled by that of the direct current, and the attraction on the arm is reduced. The arm thus vibrates at the frequency of the a.c. supply (reference) voltage. Most choppers use a permanent magnet in place of the d.c. winding.



55.32

Figure 4-17.—Electromechanical vibrator (chopper).

To reduce the power required to drive the arm, the arm is usually tuned so that it vibrates naturally at the proper frequency. The output is then a square wave, having the level of the d.c. input for one-half cycle and zero level for the other. Blocking capacitors in the amplifier that follows the chopper remove the d.c. component, so that the signal becomes a square wave with an amplitude proportional to the d.c. signal level and a phase which reverses when the d.c. signal changes polarity. This amplifier also discriminates against high frequency signals, so that the square wave ultimately is converted to a sine wave at the frequency of the vibrator switching.

If the motion of the vibrator arm is synchronized so that the contacts make and break in phase with the reference a.c. voltage, the vibrator's output voltage will be in phase with the reference voltage.

In some applications a phase shift is introduced by the vibrator. The vibrator arm is synchronized one-quarter cycle after the peak of the a.c. reference voltage. Thus the vibrator output will lag the reference voltage by 90 degrees. The error signal entering the amplifier contains the 90-degree phase shift necessary to start or stop a split-phase servomotor.

In some servos a vibrator is not only used to change d.c. to a.c., but is also used as a subtraction device. Suppose the vibrator input terminals were supplied with two signals, one equal to plus five volts and the other equal to minus five volts. The vibrating contact will move between the two points, which differ in potential by ten volts. The output of the vibrator is proportional to the difference in potential between the vibrator's inputs. In this example, the circuit output would be a square wave with an amplitude of ten volts peak to peak. Recall that a servo's error detector will measure the voltage difference between the ordered signal and the response signal. This is exactly what the vibrator is doing.

Crystal Diode Modulator

The crystal diode modulator (fig. 4-18) consists of a diode bridge and transformer network.

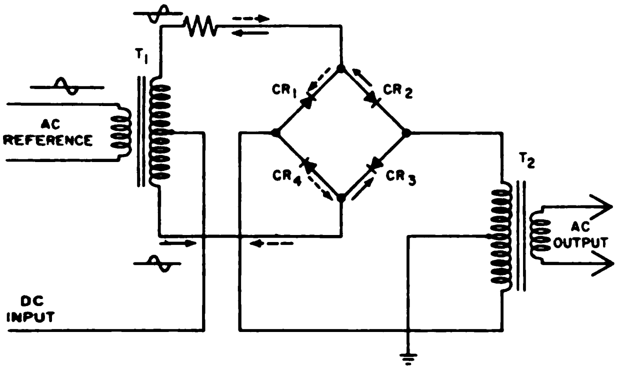


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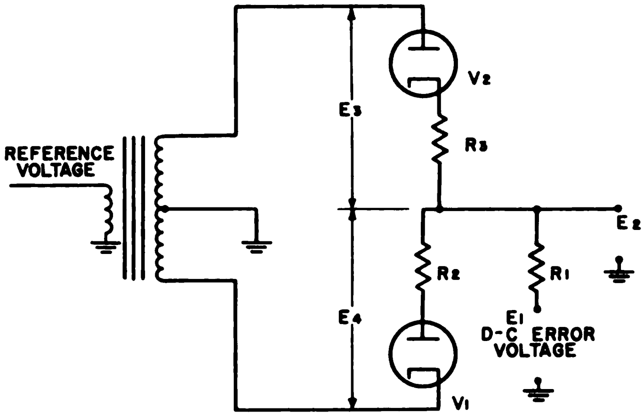
Figure 4-18.—Crystal diode modulator.



55.34
Figure 4-19.—Electron tube modulator.

When a reference voltage is applied to transformer T1, diodes CR2 and CR3 conduct during the negative alternation of the reference voltage. (There is a 180° phase reversal in T1.) Conversely, diodes CR1 and CR4 conduct on the positive half-cycle of the reference voltage. Electron flow during the positive and negative alternations is represented by dotted arrows and solid arrows, respectively. If a positive d.c. signal voltage is applied during the negative-going alternation, electrons will flow from ground, through the upper half of the primary winding of transformer T2, through diode CR2 and through the upper half of the secondary winding of transformer T1 to the d.c. source. Current flow through the bottom of T2, CR4, and the bottom of T1 secondary is opposed by the opposite polarity across CR4. On the positive-going alternation, electrons will flow from ground, through the lower half of the primary of transformer T2, through diode CR4, and through transformer T1 to the d.c. signal source.

If a negative d.c. signal is applied, electron flow through the circuit will be reversed. That is, electrons will flow from the d.c. signal source, through diodes CR3 and CR1 in turn, to ground. Since, in all cases electrons are caused to flow through the primary of transformer T1 at the rate of the reference voltage, the output of this transformer will be at the frequency of the reference voltage. The phase of the a.c. output signal is determined at any given instant by both polarity of the d.c. input and the phase of the a.c. reference voltage.

Electron Tube Modulators

An example of an electron tube modulator is shown in figure 4-19. The input d.c. error voltage is impressed between E1 and ground. The a.c. reference voltage along with the action of V1, V2, R2, and R3 effectively clamp output E2 at zero potential for one-half cycle of the reference voltage. To accomplish this, the following conditions must exist:

1. R1 must be much larger than R2.
2. R2 and R3 are equal.
3. V1 and V2 must be matched (usually a balance circuit is included to match the tubes).

With a reference voltage applied, making the plate of V2 positive and the cathode of V1 negative, current will flow through V1, R2, R3, and V2. Since R2 equals R3, voltage E3 will equal E4.

If the d.c. error voltage is positive, V1 will pass current down across R1, effectively dropping the amount of the error signal. The voltage output at E2 for this half cycle will be zero. If the d.c. error voltage is negative, current will pass up across R1, R3, and through V2 to the source. R1 once again (because of its size) drops an amount almost equal to the d.c. error voltage and the signal at E2 will again be almost zero.

We can readily see that when the tubes conduct, the voltage at E2 will be almost zero, and when they are cut off by the reverse polarity of the reference voltage, the output voltage will be equal to the d.c. error input. This will result in a pulsating d.c. output with its amplitude and phase determined by the amplitude and polarity of the d.c. error voltage.

DEMODULATORS

Some servosystems use d.c. servomotors to drive the load. A typical example is the amplidyne system. The input signal to an amplidyne servo is usually an a.c. synchro voltage. This requires that the a.c. order signal be converted to a d.c. signal. To accomplish this a demodulator circuit is used. Demodulation is the process of extracting the signal intelligence from a modulated carrier wave. In the amplidyne type servo the modulated carrier wave is the a.c. signal from the CTs. The magnitude of the a.c. signal is proportional to the size of the error and the phase of the intelligence we must extract.

To derive a d.c. signal having the same intelligence as the a.c. signal we must be able to detect both the phase and the magnitude of the a.c. signal. The polarity of the d.c. signal is determined by the phase of the a.c. signal compared to a reference voltage. The reference voltage must be from the same source as the synchro supply, which is the voltage we modulated in the first place. The magnitude of the d.c. signal is directly proportional to that of the a.c. signal.

Demodulators are often referred to as phase-sensitive rectifiers or detectors, phase-discrimination converters, or simply as discriminators and detectors.

Diode Demodulators

A typical diode demodulator (phase detector) is shown in figure 4-20. As illustrated, an a.c. supply voltage serves as the reference voltage for the detector. This voltage must come from the same source that is supply a.c. excitation to the synchro system, or whatever type of error detector is used, and must be in phase with the common supply voltage. This permits a phase-comparison of the error voltage with the reference voltage. The plates of the two diodes are supplied with this reference voltage in such a manner that the two plates will be in phase. Assuming that there is no error signal from T2 to the plates of the diodes at the time the plates are on a positive half-cycle, the two diodes will conduct equally. The voltages produced across R1 and R2 are equal, making the cathode of V1 and V2 at equal potential with respect to ground. With the two output terminals at the same potential, the output voltage will remain at zero as long as no error signal is applied.

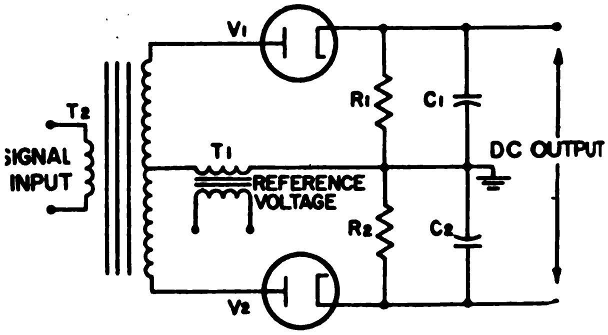


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Figure 4-20.—Diode demodulator.

If an error signal is supplied to T2 making the plate of V1 positive at the same time the reference voltage on the plates of V1 and V2 is on its positive half-cycle, V1 conduction will be increased and V2 conduction decreased over the no-signal condition. Since the voltages applied to the plates are both alternating, the voltage developed across R1 and R2 would also be alternating. However, R1-C1 and R2-C2 have a long time constant compared to the input frequency, and therefore filter most of the ripple, giving a d.c. output.

If the error signal applied to T2 is changed by 180 degrees, V2 would now increase its conduction while the conduction of V1 would be reduced. This would result in an output voltage of reversed polarity. Variations of the diode phase detector may be encountered; however, they all depend on the same basic principles of operation.

Triode Demodulator

The demodulator shown in figure 4-21 is a full-wave phase-sensitive demodulator. It compares an a.c. signal voltage with an a.c. reference voltage to produce a d.c. output. In this circuit there are two sets of conditions for the polarities of the input voltages, since at any instant of time the reference voltage and the signal voltage will be in phase or 180° out of phase.

An in-phase condition is shown in figure 4-21. An examination of the existing instantaneous polarities reveals that only V1 can conduct. Each

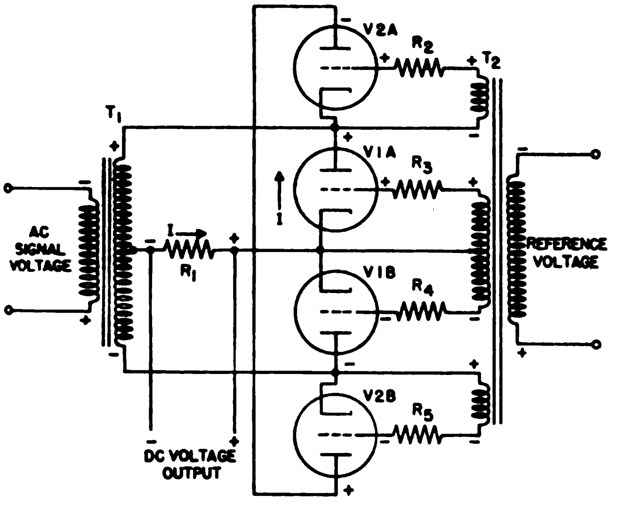

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Figure 4-21.—Triode demodulator.

section of V1 will conduct on alternate half-cycles of input voltages. This is approximately the action of a full-wave rectifier.

Consider the instantaneous polarities present:

1. V2A is not conducting because its plate is negative.
2. V2B is not conducting because of the negative bias on its grid; the windings of T2 bias it below cutoff.
3. V1B is not conducting because its plate is negative.
4. V1A is conducting because both plate and grid are positive with respect to the cathode. The current, I, will flow through the tube and resistor R1 as shown, producing the output d.c. voltage across R1.

On the alternate half-cycle of the a.c. voltages, V1B will conduct and the d.c. current through R1 will be in the same direction as before.

For the reverse condition, when the a.c. voltages are 180° out of phase, V2 will conduct. The d.c. output voltage across R1 will reverse its polarity.

Electric Demodulator

The demodulator shown in figure 4-22 will rectify an a.c. signal and convert it to a pulsating d.c. signal proportional in magnitude to the input signal voltage. The polarity of the d.c. output voltage is determined by the phase of the signal compared to the reference voltage.

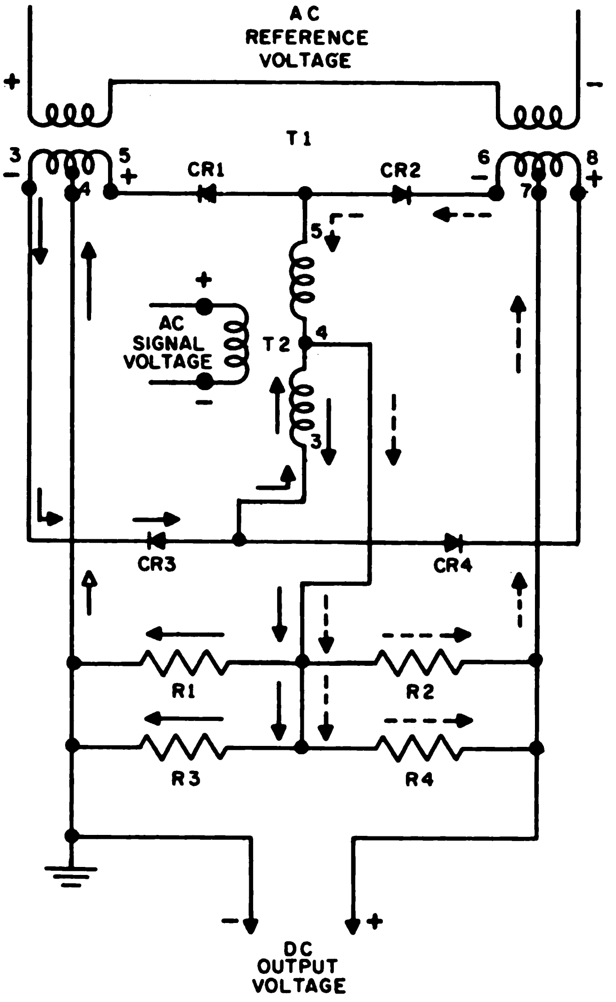

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Figure 4-22.—Electric demodulator.

Assume that the signal voltage on transformer T2 is in phase with the reference voltage on transformer T1. In the half cycle shown the current depicted by the dotted arrows starts at terminal 6 of T1, flows through the rectifier CR2, winding 5-4 of T2, and parallel resistors R2 and R4, to terminal 7 of T1. The signal and reference voltages in these secondary windings of the transformers are in additive series. Therefore, the voltage across the parallel resistors is proportional to their sum.

The current depicted by the solid arrows starts at terminal 3 of T1, flows through rectifier CR3, winding 3-4 of T2, and parallel resistors R1 and R3, to terminal 4 of T1. The voltages in both these transformer windings are in subtractive series. Therefore, the voltage across the resistors is proportional to their difference.

Consequently, the voltage across resistors R1 and R3 is smaller than the voltage across the resistors R2 and R4. The resultant voltage across the resistor network and at the output terminals is the algebraic sum of the two voltages. The polarity of the output voltage is the same as that of the greater voltage.

On the next half cycle the signal and reference voltages are still in phase. You should be able to trace the current flow in the demodulator mentally without the use of arrows. Start at terminal 5 of T1 which is now negative, through CR1, winding 5-4 of T2, and parallel resistors R1 and R3, to terminal 4 of T1, which is now positive with respect to terminal 5. The voltages are still in subtractive series.

In the other pair of windings start at terminal 8 of T1, which is now negative. From terminal 8, the current flows through CR4, winding 3-4 of T2, and the resistors R2 and R4, to terminal 7 of T1, which is now positive with respect to terminal 8. The voltages in the secondary windings of T1 and T2 are still in additive series. Hence the voltage across the resistor network is the same for both half cycles and the output from the demodulator is a pulsating d.c. voltage.

If we assume the signal voltage is 180 degrees out of phase with the reference voltage the direction of the current flow through the resistor network would be reversed. The voltage across R1 and R3 would now be larger than the voltage across R2 and R4. Therefore, the polarity of the output voltage would be reversed.

The peak-to-peak value of the reference voltage is constant; therefore, the magnitude of the output is determined by the size of the error signal. With no signal present the reference voltage drop across the resistor networks would be equal and opposite, and there would be no output. This balance is disturbed by the error signal.

ELECTRON TUBE SERVOAMPLIFIERS

Figure 4-23 shows an electron tube servoamplifier with an a.c. input and a d.c. output. Transformer T1 (fig. 4-23) couples the error signal output from the rotor of the CT 180° out of phase to the grids of demodulator amplifier tubes V1 and V2. Resistors R2 and R3 serve as load resistors for V1 and V2. Resistors R1 and R4 provide negative feedback to the cathodes of V1 and V2.

Transformer T2 applies the a.c. reference voltage in parallel to the plates of V1 and V2. Capacitors C1 and C2 filter the pulsating d.c. developed across R2 and R3.

Tubes V3 and V4 are connected in a push-pull arrangement and serve as d.c. amplifiers with R5 and R6 as their cathode resistors and R7 and R8 as their plate load. Motor B1 is a d.c. servomotor which is mechanically geared to the load to be positioned and is also mechanically coupled back to the CT rotor to null the error signal.

Tubes V1 and V2 conduct only on positive alternations of the a.c. reference voltage. When the CT is in alignment with the CX there is no error signal input, and V1 and V2 conduct equally during the positive portion of the reference signal. Thus, equal voltages are developed across R2 and R3. At this point, V1 and V2 are functioning as rectifiers, and the voltage across R2 and R3 is pulsating d.c., which is filtered by capacitors C1 and C2, and applied to the grids of V3 and V4. Amplifier tubes V3 and V4 conduct equally under this conditpon, and the voltage developed across R7 is equal to the voltage across R8. Therefore, no difference in potential exists between the plates of V3 and V4 and, hence, no current flows through the armature of servomotor B1, and the motor will not rotate. When the CX rotor is moved to a new position, the CT is no longer in alignment with the CX and an error voltage output is produced by the CT which is applied to the primary of input transformer T1.

It is important to keep in mind that the a.c. reference voltage applied to the plates of V1 and V2 is from the same source as the synchro excitation voltage, and any error voltage induced into the CT rotor is either in-phase or 180° out-of-phase with the reference voltage. Assume that the angular displacement between the CX and the CT is in such a direction that the error voltage induced across the CT rotor is in-phase with the reference voltage. When the reference voltage goes positive, a positive half-cycle is applied to the grid of V1 and a negative half-cycle of error voltage is applied to the grid of V2 (remember that T1 is effectively a push-pull transformer). The conduction of V1 increases and, therefore, an increased voltage drop occurs across R2. This voltage is filtered

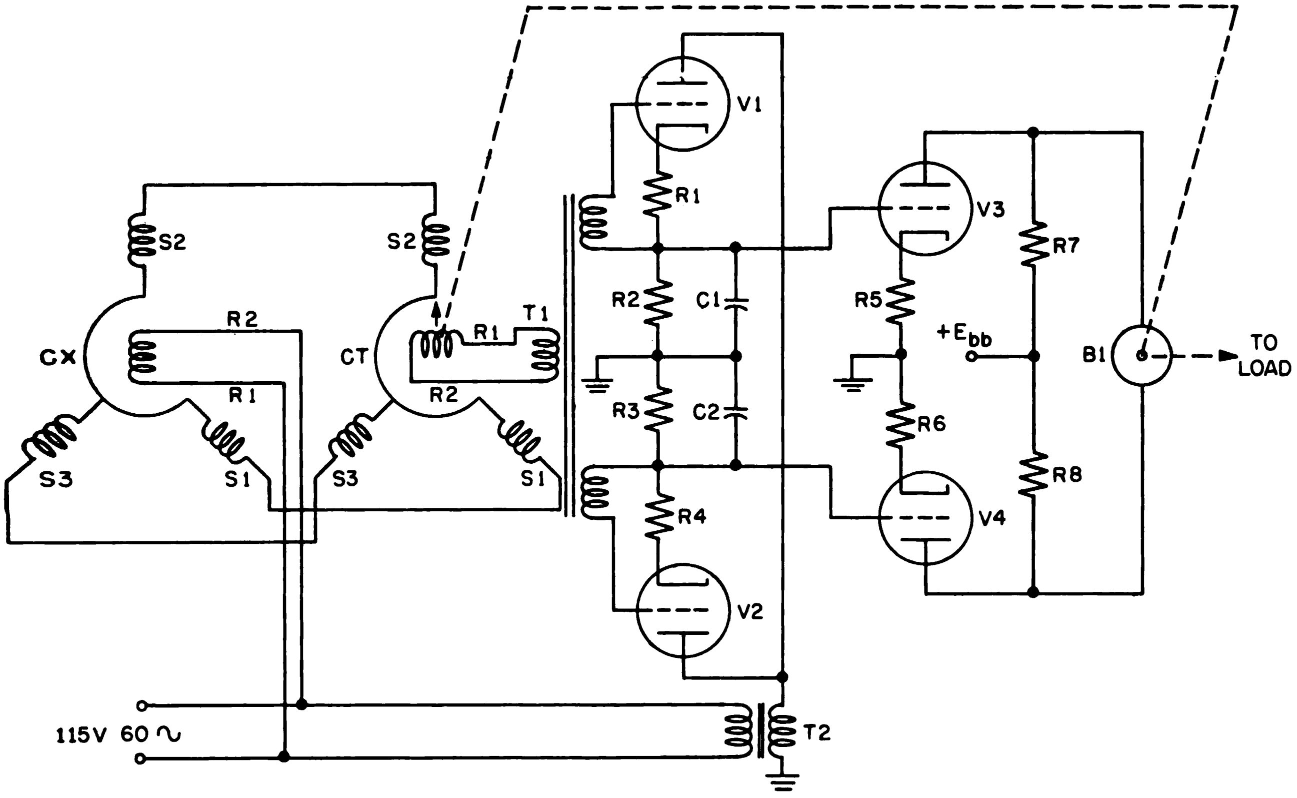

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Figure 4-23.—Servo using electron tube servoamplifier.

by C1 and applied to the grid of d.c. amplifier V3, causing the conduction of V3 to increase. At the same time, the negative half-cycle of error voltage applied to the grid of V2 decreases conduction of V2, causing a decreased voltage drop across R3, and consequently the d.c. voltage coupled to the grid of V4 decreases, reducing the conduction of V4. Since the conduction of V3 increased, while the conduction of V4 decreased, a difference in potential now exist between the plates of V3 and V4 due to the increased voltage drop across R7, and the decreased voltage across R8. Current now flows from the plate of V3 through the armature of servomotor B1 to the plate of V4 and the motor rotates driving the load in the desired direction. Tubes V1 and V2 conduct only during the positive half cycle of the a.c. reference input. Servomotor operation, however, is not erratic since filter capacitors C1 and C2 maintain fairly constant voltages across the grids of V3 and V4, causing the amplifier output to be fairly constant. The servomotor being mechanically connected through gears to the CT rotates the CT rotor toward the position of alignment with the CX. As the angular displacement between the CT rotor and the CX rotor diminishes, the error voltage produced by the CT diminishes and the d.c. output of the servoamplifier decreases, causing the servomotor to rotate slower. When the CT reaches the same bearing as the CX, servomotor rotation ceases because no error voltage is produced by the CT, and consequently, there is no longer an output from the servoamplifier.

If the CX is rotated in the other direction, the resulting error voltage produced by the CT is 180° out of phase with the reference voltage. Circuit operation is the same, but the polarities are reversed. Tube V1 is driven negative causing a negative voltage to be applied to the grid of V3, and the voltage on the plate of V3 increases. Tube V2 is driven positive causing a positive voltage to be applied to the grid of V4, and the voltage at the plate of V4 decreases. Current flows from the plate of V4 through the armature of servomotor B1 to the plate of V3, causing the servomotor to rotate in the direction opposite to the direction that it rotated previously.

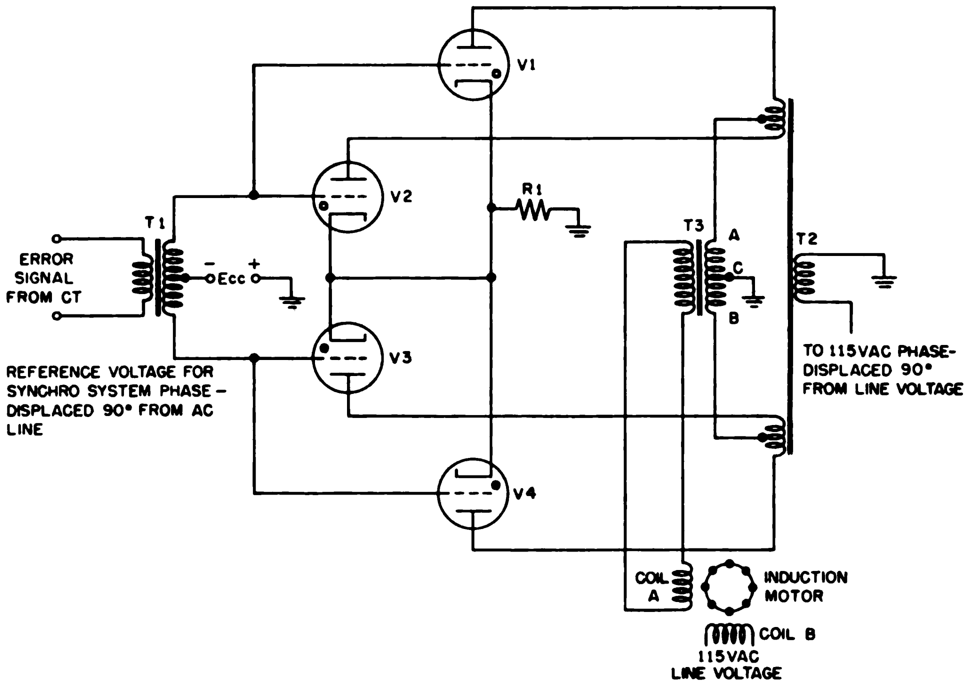
Thyratron tubes are often used in servoamplifiers as they can pass a much greater current than the vacuum type electron tube. Figure 4-24 shows a simplified schematic diagram of a thyratron servoamplifier. Four thyratrons are used; two of which operate on each half-cycle to drive a two-phase a.c. servomotor.

The error signal from the CT (fig. 4-24) is coupled to the grids of the thyratron tubes by transformer T1. A negative source of bias is also connected to the grids through the center tap of the secondary winding of transformer T1. This bias prevents the thyratrons from firing when there is no error signal input. Transformer T2 applies plate voltage, phase-displaced 90° from the line voltage, to the plates of all four thyratrons. The two secondary windings of T2 are arranged so that the plate voltage of V1 and V4 is in phase with the plate supply, and the plate voltage of V2 and V3 is 180° out-of-phase with the plate supply.

Coil A of the servomotor is energized by induced voltage in the secondary of transformer T3. The primary of T3 is supplied from the centertaps of the two secondaries of T2. This supply is phase-displaced 90° from the line voltage; therefore, the magnetic fields of coils A and B will be 90° out-of-phase each time coil A is energized.

With no error signal input, the thyratrons will not conduct; there will be no output signal to the servomotor; and the servomotor shaft will not rotate. If an error signal is applied, the thyratrons will conduct, and the output signal will drive the servomotor.

If an error voltage with an instantaneous positive polarity appears at the top of the T1 secondary and at the same time the V1 plate swings positive, V1 fires. Thyratron V2 cannot fire because its plate is negative, and V4, having an additional negative bias, remains cut off. As long as the error voltage maintains this phase relationship, V2 and V4 cannot fire. On the first alternation, current flows through T3 from A to C. On the following alternation, both grid and plate of V3 swings positive, and V3 fires with a plate current flow from B to C in T3. Thus, V1 and V3 conduct on alternate half-cycles, causing an a.c. voltage to be induced in the T3 secondary. This voltage may be either in


V1
V2
R1
T1
ERROR SIGNAL FROM CT
- +
Ecc
T3
A
C
B
T2
V3
REFERENCE VOLTAGE FOR SYNCHRO SYSTEM PHASE-DISPLACED 90° FROM AC LINE
TO 115VAC PHASE-DISPLACED 90° FROM LINE VOLTAGE
V4
COIL A
INDUCTION MOTOR
COIL B
115VAC LINE VOLTAGE

175.30
Figure 4-24.—Thyratron servoamplifier.

phase with the reference voltage or 180° out-of-phase. The servomotor now turns in the ordered direction. Reversal of the error voltage phase causes V2 and V4 to become the conducting thyratrons and shifts the controlled phase 180° with respect to the reference voltage. Thus, the servomotor reverses its direction of rotation.

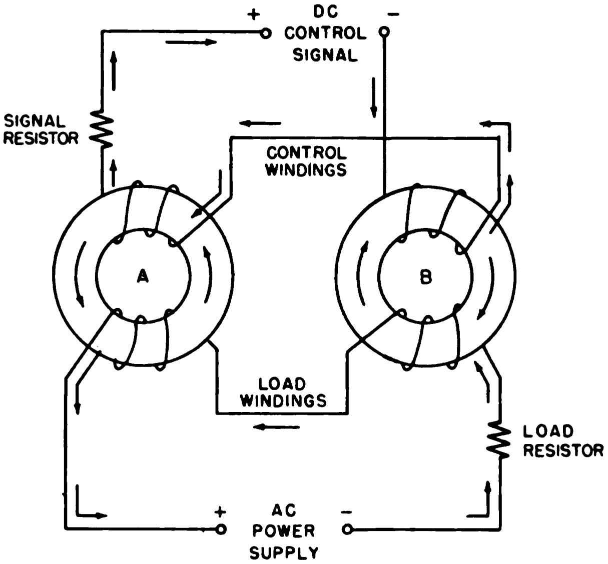
MAGNETIC SERVOAMPLIFIERS

In electron tube amplifiers the amount of current that flows through a tube is controlled by its internal impedance. A reduction of the impedance will increase the current flow through the tube. Magnetic amplifiers use the same principle. The impedance, and consequently the current in a saturable reactor can be controlled by varying the magnetic state of its core. Magnetic circuits are covered in Basic Electricity, NavPers 10086-(rev.).

Basic Saturable Reactor

Basically, the saturable reactor circuit has a control winding and a load winding on each of two toroidal cores (fig. 4-25). The control windings are connected so that their magnetic fields have opposite polarities. The signal resistor has a low ohmic value and the control windings have a small number of turns. The load windings present an infinite impedance when there is no signal input to the control windings, and the load current is practically zero.

A d.c. control signal impressed on the control windings will create magnetic fields in cores A and B. The magnetic fields will be stationary and opposite in polarity. The fluctuating magnetic fields created by the a.c. power supply have the same polarity in both cores and will be additive in one core and subtractive in the other core with the control magnetic fields. When the a.c. power during its first half-cycle creates additive fields in core B and subtractive fields in core A, there is a point where core B becomes saturated. The load winding on core B immediately drops towards zero impedance because, with constant flux density, there is no change in turns-linkage as the a.c. voltage varies. At the same time the impedance of the load winding of core A is considerably reduced. The subtractive magnetic fields reduce the total flux density until there is only a small rate-of-change of turns-linkages as the a.c. voltage varies. With low total flux density the windings on core A begin to function as a transformer. At this point, the control windings appear as a short circuit, and the impedance of the load windings is reduced further toward zero. Therefore, almost the entire voltage of the a.c. power supply is impressed on the load resistor.



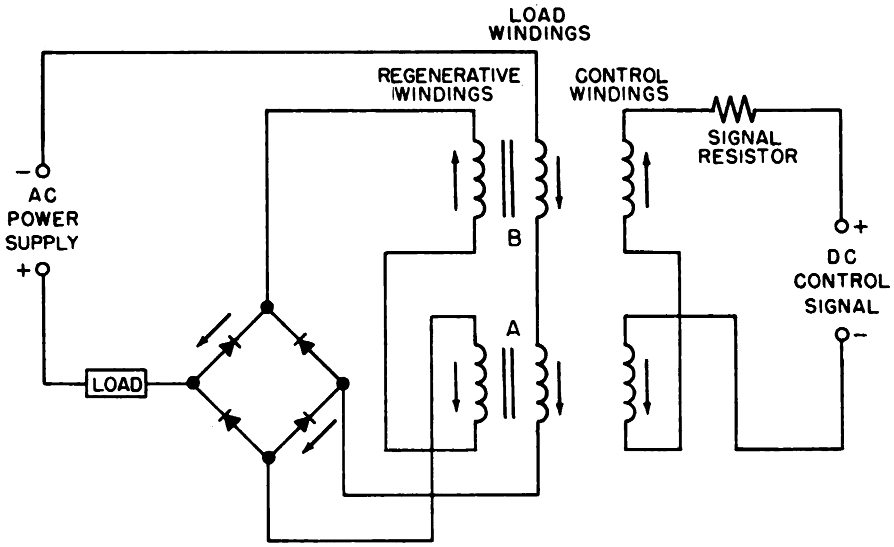
166.23
Figure 4-25.—Basic saturable reactor.

During the second-half-cycle of the a.c. supply, core A becomes saturated and core B functions as a transformer. The load resistor receives almost the entire voltage of the a.c. supply, but of the opposite phase. The amount of current through the load resistor is determined by the point in the a.c. cycle when one of the cores becomes saturated. The saturation point is determined by the d.c. control signal's amplitude. When the d.c. signal is greater, saturation is reached earlier and the period that load current flows in each cycle lengthens. Thus more current is used at the load.

The basic saturable reactor circuit does not have the stability or accuracy required for use in magnetic amplifiers for servosystems. To obtain better operation, the reactors have several additional windings. A regenerative winding is used with the load winding, and a bias and a negative feedback winding are used with the control windings.

Regenerative Windings

The load windings are connected in series to a full-wave rectifier bridge (fig. 4-26). The



166.24
Figure 4-26.—Regenerative windings.

regenerative windings are connected in series bucking across the bridge. When a d.c. control signal is present, during the first half-cycle of the a.c. supply voltage, the current through the regenerative windings will create a magnetic field of the same polarity as created by the load and control current in one core. This core (A in the figure), will drive quickly to saturation and cause the impedance of the load winding to drop to near zero. At the same time, the magnetic fields created in the other core (B in the figure) by the load and regenerative windings, tend to cancel each other leaving only the low density flux created by the d.c. control signal. This core will act as a transformer, in which the near zero impedance of the control winding is reflected in the load winding.

In the second half-cycle of the a.c., the current direction remains the same, except through the load windings and the load. Core B becomes saturated, and load winding B has near zero impedance. Load winding A now acts as the transformer.

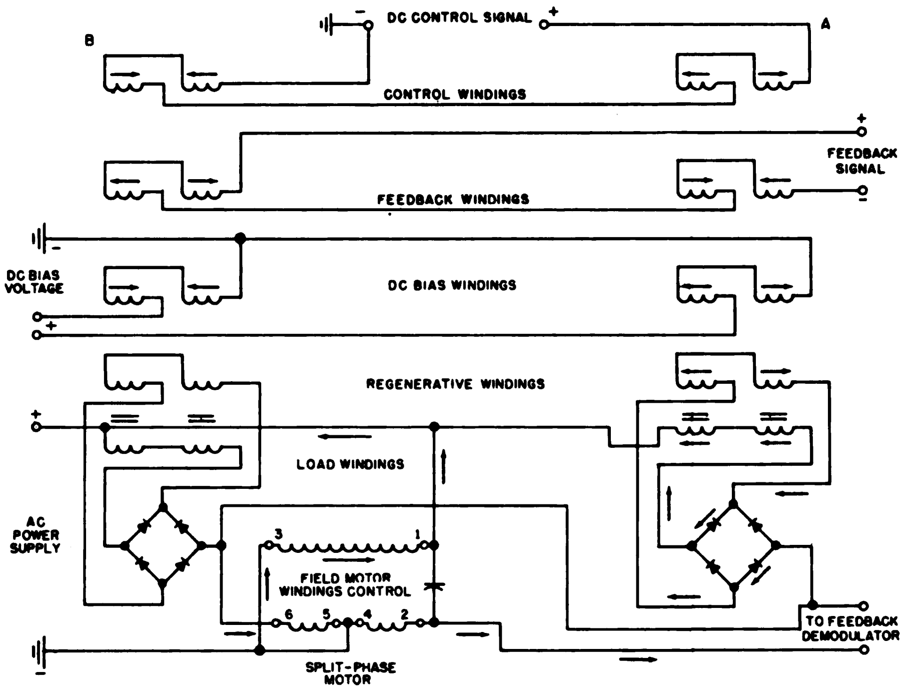
Magnetic Amplifier In A Servo

Figure 4-27 shows a practical bidirectional servo with a magnetic amplifier consisting of two saturable reactors. One-half the control winding of the a.c. servomotor acts as the load on each reactor. The direction of the motor rotation is determined by selecting the half of the control winding through which current will flow. The saturable reactors A and B are similar to the one in figure 4-26 with the exception that we have added the bias and negative feedback windings.

Bias and Feedback Windings

The efficiency and accuracy of a magnetic amplifier are lowered by the magnetic hysteresis of the core material. Hysteresis is the lag of the magnetic flux behind the current that causes it. The two bias windings in each reactor are wound in opposite directions. Therefore, the magnetic fields created by the d.c. bias current have opposite polarities. To counteract the lag, the bias magnetic fields tend to cause the magnetic fields in the core to reverse polarities with the a.c. voltage supply. The amplitude and direction of the bias current is set so that when the control signal has the same polarity it will prevent reactor B in the figure from saturating. When the bias and control signals have opposite polarities, the bias will stop reactor A from conducting.

The d.c. control signal (fig. 4-27) is positive, and saturable reactor A will conduct. The



166.25

Figure 4-27.—Magnetic servoamplifier.

direction of current flow through the motor's control winding 2-4, which is the load on the reactor, corresponds to the current in the motor's field winding 1-3. During the negative half-cycle of the a.c. supply the current in both the control and field windings of the motor will reverse. Therefore, the motor will continue to drive in the same direction. Basically, the operation of the saturable reactor is identical to the one in figure 4-25. As long as the input control signal polarity remains the same, reactor A will continue to conduct. Reactor B is prevented from conducting by its bias voltage.

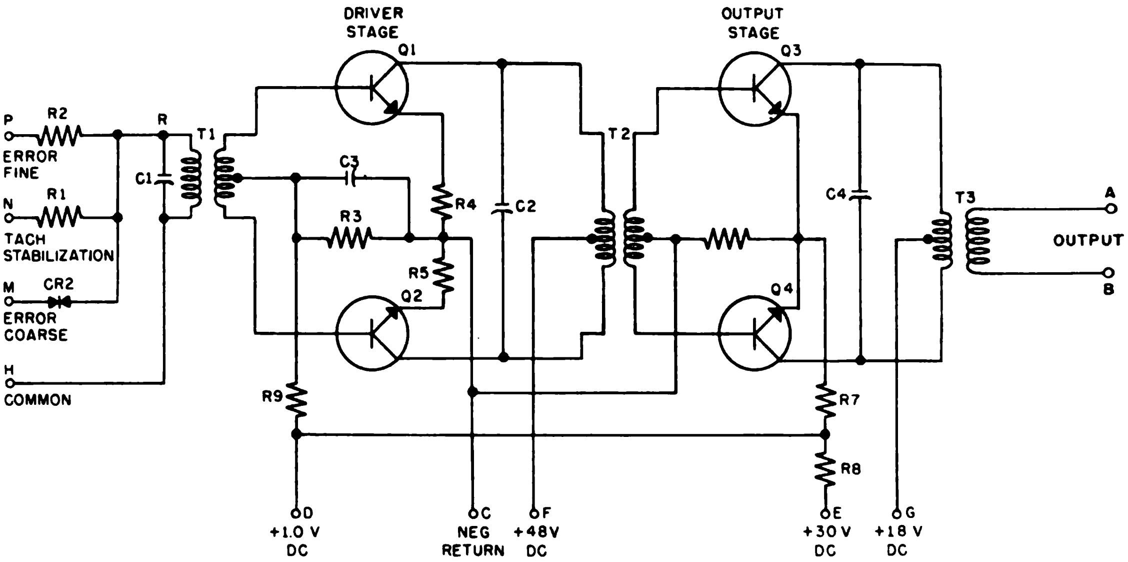
If the polarity of the input signal becomes negative, reactor B will conduct and pass current through motor control winding 5-6. Current direction through the motor control winding is opposite to that in the motor field winding. The motor will now rotate in the opposite direction. Reactor A is prevented from saturating by its bias current. Thus we have a bidirectional servosystem.

The negative feedback voltage is taken from the output motion of the servo. Its polarity is opposite to that of the control signal voltage input to the amplifier. The feedback voltage serves the same purpose as in an electron tube amplifier. It will dampen the servo, reduce the output noise, and provide system stabilization.

SEMICONDUCTOR SERVOAMPLIFIERS

Figure 4-28 shows a two-stage transistor servoamplifier of the plug-in module type. The input error signals on pins P and M are from a dual-speed synchro control system. Zener diode CR2 is part of the synchronizing circuit and works as two diodes connected back to back. The fine signal on pin P is normally in control. If the coarse signal becomes sufficiently large it will break down the diodes and assume control. The input on pin N is a feedback voltage from a tachometer generator which provides system stabilization. (Stabilization is discussed later in this chapter.)

The sum of the voltages on pins P, M, and N is applied to the input transformer T1. The other terminal of T1 is connected to pin H, which is a common return for the CTs and the



166.21
Figure 4-28.—Transistor servoamplifier.

tach. There are four supply voltages—the +1 VDC and the +30 VDC are used in a bias network, the +48 VDC is used as collector supply for the first stage, and the +18 VDC is used as the collector supply for the output stage.

Resistors R3, R6, R7, R8, and R9 form a voltage divider network to provide a fixed base-emitter bias on the transistors. The circuit for the +1 V bias is from pin D through R9 and R3 back to the negative side of pin C. The bases of Q1 and Q2 are connected to the bias circuit at the tie point between R9 and R3 through the winding of the input transformer T1. Because of the need for good voltage regulation, it is desirable not to have current flow in this circuit. Therefore, the +1 V bias circuit is connected to the +30 V bias circuit at the junction of resistors R7 and R8. There is approximately +1.0 volts at this junction and most of the current drawn by the base-emitter circuit comes from the +30 VDC source. Consequently, the +1 V bias supply is not loaded down and voltage regulation is good.

The circuit for the +30 bias voltage is from pin E through R8, R7, and R6 back to the negative side on pin C. The base Q3 and Q4 are connected to the bias circuit through the winding of T2, the interstage transformer. The +30 bias voltage is connected to the +1 V bias voltage at the junction of R8 and R7. Thus in the biasing circuits, R9 and R3 are in parallel with R7 and R6.

The collectors of the first stage transistors, Q1 and Q2 are connected to the +48 volt supply at pin F through the primary winding of T2. The error signals from the opposite ends of T1 to the bases of Q1 and Q2 are 180 degrees out of phase with one another. The output from this stage is from the collector, which is connected to the primary of T2 in opposition. The stage is arranged in push-pull as a driver for the second stage. The transistors are arranged in a bases input—collector output circuit, with grounded emitters. The emitters are connected through R4 and R5 to the negative side. The resistors R4 and R5 furnish self-bias and help to stabilize the transistor circuits.

Transformer T2 couples the amplifier error signal to the second stage. Transistors Q3 and Q4 are base input—collector output, and are connected as a push-pull grounded-emitter circuit in an arrangement similar to the first stage. The required signal inversion is obtained from the transformer. The output of the amplifier, at pins A and B, is connected to a split-phase servomotor. The motor drives the load and the feedback tachometer generator. Response from the motor repositions the CTs to null out the error signal.

In the servo we have an a.c. signal and motor with a d.c. amplifier. The d.c. voltages to the transistor's collectors are unfiltered and contain a ripple that is in phase with the reference voltage of the synchro system. Therefore, the error signal is either in phase or 180 degrees out of phase with the a.c. component in the collector voltages. This eliminates the need for a separate demodulator and modulator circuit.

Silicon controlled rectifiers (SCRs) are used as power amplifiers in some modern servosystems. The SCR as discussed in Basic Electronics, NavPers 10087 (rev) is a four-layer semiconductor rectifier that normally acts as an open circuit, but switches rapidly to a conducting state when an appropriate gate signal (pulse) is applied to the gate terminal. The SCR operates similar to the thyratron tube and can handle large amounts of power. Figure 4-29 shows a simplified block diagram of a semiconductor servosystem in which an SCR power amplifier is used to control a 30 horsepower d.c. servomotor.

Coarse and fine CT signals are fed into the crossover network (fig. 4-29). The signal output from the crossover network is demodulated, summed with a rate stabilization signal from the rate generator, and applied to the input of a transistor d.c. amplifier. The d.c. amplifier amplifies the error signal output from the summing network to the required level to control the unijunction firing circuits.

Unijunction transistors (UJTs), discussed in Basic Electronics, NavPers 10087 (rev), provide the trigger pulses to the gates of the SCRs to control the SCR power amplifier output. Two groups, consisting of three UJTs in each group, function to convert the amplified d.c. error signal into trigger pulses for six SCRs (three forward and three reverse) in the SCR power amplifier.

The SCR power amplifier supplies rectified a.c. line voltage to the servomotor. Two SCRs connected in inverse parallel are connected in each phase of the secondary of a 3-phase transformer as shown in figure 4-30.

When a positive order signal is generated, the positive group of UJTs applies pulses to the gates of SCR1, SCR3, and SCR5. These SCRs then conduct and supply rectified line voltage to the servomotor causing the motor to rotate.

When a negative order signal is generated, the negative group of UJTs supply pulses to the gates of SCRs 2, 4, and 6 which supply rectified line voltage of opposite polarity to the servomotor causing the motor to rotate in the opposite direction.

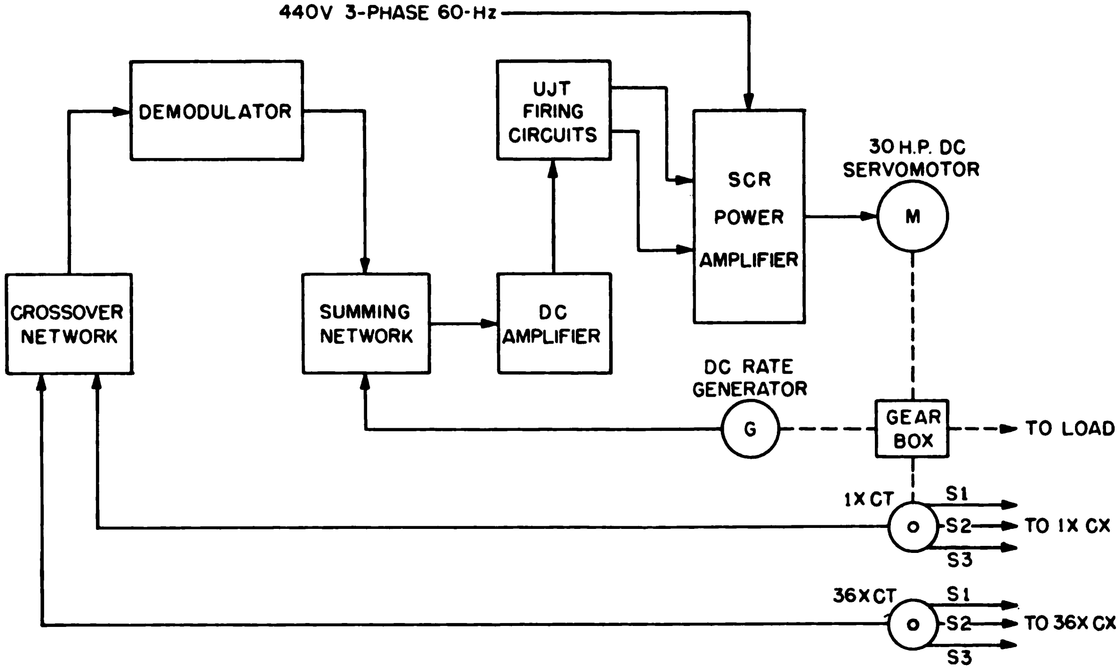


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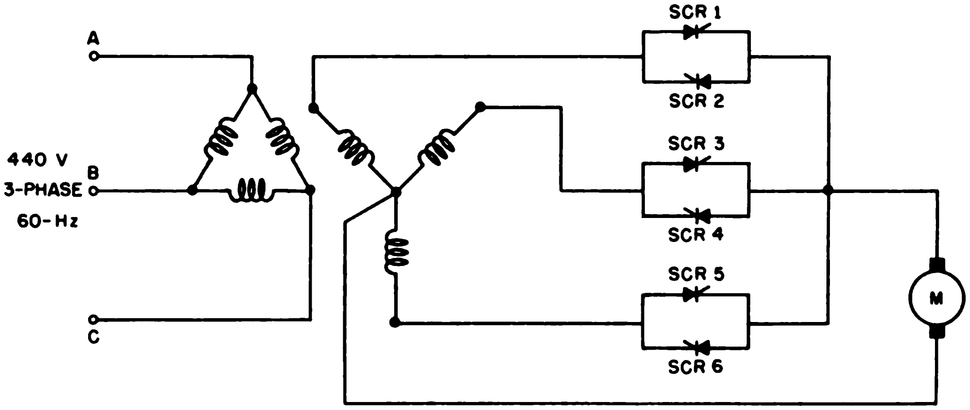
Figure 4-29.—Servo using SCR power amplifier.



175.32
Figure 4-30.—SCR power amplifier.

AMPLIDYNE SERVO POWER AMPLIFIER

As discussed in chapter 1, the amplidyne generator is a rotary power amplifier, and is used in servosystems requiring a high power output. A simplified diagram of a servosystem using an amplidyne is shown in figure 4-31.

The amplifier in the diagram rectifies and amplifies the a.c. error signal. The output stage of the amplifier is arranged in push-pull. Thus, the output of the amplifier is two opposing d.c. currents which furnish the control currents for the amplidyne control fields thereby controlling the magnitude and polarity of the amplidyne output.

A conventional 3-phase a.c. induction motor drives the amplidyne in one direction at a constant speed. The amplidyne generator excitation is supplied by the control windings F1-F2 and F3-F4. The control windings are energized by the opposing d.c. currents from the amplifier. These windings create a magnetic field which is the resultant of both currents. With a zero error signal to the amplifier, the d.c. outputs are equal and opposite. Therefore, they cancel and no control field is present in the generator. When there is an error signal to the amplifier, one or the other of the d.c. currents will increase while the other will decrease a like amount, and a resultant magnetic control field will be present in the generator.

The control field causes a relatively large current in the armature winding shorted by the brushes. This armature current creates a strong quadrature field. The unshorted armature windings cut the quadrature field causing a large current in the windings. This current is delivered to the servomotor by the load brushes.

The magnitude of the amplidyne output is determined by the strength of the control field. The polarity of the amplidyne output is determined by the polarity of the control field. Thus, both the magnitude and polarity of the amplidyne output are determined by the d.c. current outputs from the amplifier.

The servomotor is a separately excited d.c. motor of conventional design; the field being supplied by a separate exciter generator.

As the servomotor has a steady excitation field, the direction of rotation depends only on the direction of the current in the armature. The turning force, or torque, developed by the motor depends on the magnitude of this current. Therefore, the motor's direction of rotation and torque depend on the output of the amplidyne generator.

ELECTROHYDRAULIC SERVOSYSTEMS

Hydraulic components are frequently used in Navy servosystems. Hydraulic power devices, such as motors and associated control valves, have an advantage of a response much faster than the best electric motors. They also require a minimum of maintenance, have very high accuracy, and are well adapted to heavy loads.

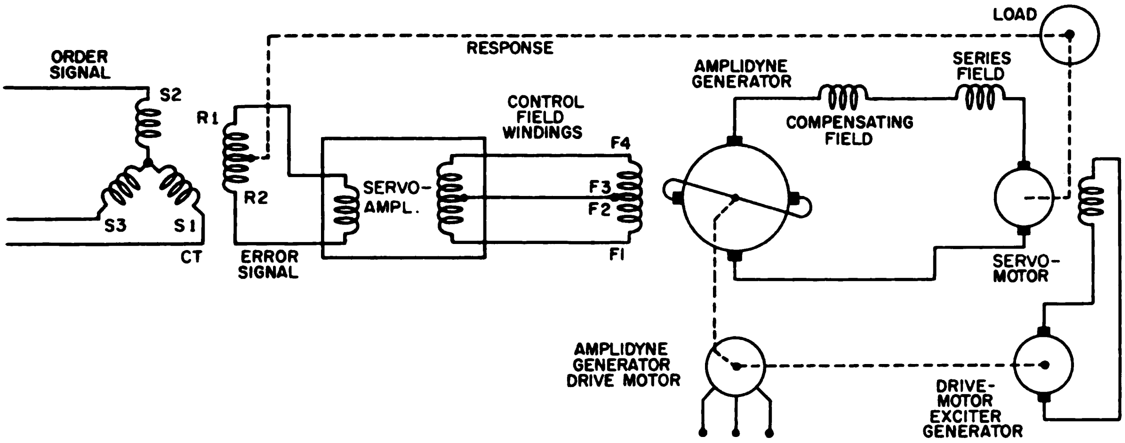


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Figure 4-31.—Servosystem using amplidyne generator.

The essential components of a hydraulic system are:

1. Source of high pressure oil and sump to receive discharged oil.
2. Control valve and means of employing an actuating signal.
3. Actuator (motor or cylinder).

The theory of operation of a hydraulic system is discussed in Fluid Power, NavPers 16193-A.

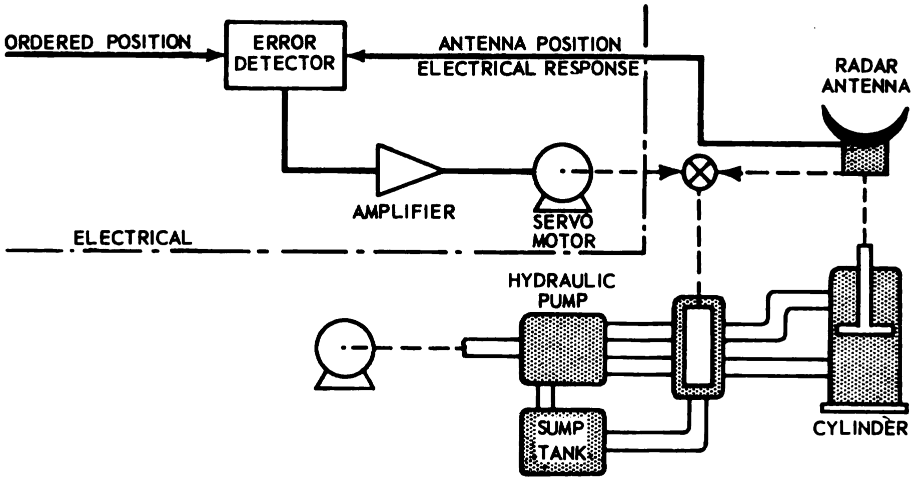
The source of high pressure oil serves as a source of power to operate the actuator. However, this source of power is controlled by the control valve. This valve is actuated by the output from the servoamplifier. This control is normally accomplished by feeding the error signal to a solenoid controlled valve. However, the error signal could be used to drive an electric motor which, in turn, actuates the control valve. The actuator is usually in the form of an axial motor which must be a reversible and variable speed type. Some applications may employ a cylinder where linear motion is required for positioning.

Figure 4-32 shows a simplified diagram of a radar antenna position system. The electrical section of the drive is a typical electromechanical servo. The output of this section, however, does not move the antenna directly, but is used to control the hydraulic section of the drive. The servo motor controls the movement of the servo valve through a mechanical differential linkage.

The servo valve governs the flow of the high-pressure hydraulic oil to the antenna positioning cylinder. In its neutral position the servovalve blocks the flow of hydraulic oil to the cylinder. The high-pressure oil trapped in the upper and lower chambers of the cylinder forms a hydraulic lock on the piston. The pistons, hence the antenna, are frozen in their positions by the lock.

When the servomotor moves the servovalve from its neutral position, one of the cylinder chambers will be connected to the high-pressure line. The direction in which the servovalve is moved by the motor determines which chamber is connected to the high-pressure line. Movement of the valve connects the opposite chamber to the sump tank to allow the oil in the chamber to drain off. The high-pressure oil forces the piston in the cylinder to move. The speed at which the piston will move is determined by the rate of delivery of the oil to the chamber. This is determined by the amount the servovalve is moved from its neutral position. The total movement of the piston (antenna), is determined by the volume of oil to the chamber. This in turn is determined by how far the servovalve is moved from its neutral position, and how long it remains off its neutral position.

Response from the antenna is used to bring both the electrical and the hydraulic systems to their null positions. This makes sense since both systems must stop driving when the antenna is at the desired position. If the response voltage from the antenna is equal and opposite to the input signal voltage, the electrical signal error is zero. The output of the amplifier to the



12.289
Figure 4-32.—Simplified diagram of an electrohydraulic servo.

servomotor is zero, and there will be no torque on the motor. The hydraulic system is at null when the servovalve is in its neutral position. Mechanical response feeds through the differential linkage to zero the servovalve as the antenna moves. Thus the input to the servovalve is proportional to the difference between the movement of the servomotor and the movement of the antenna.

SERVO OPERATIONAL ACCURACY

A servo should drive rapidly to a fixed correspondence point. It should synchronize with a minimum of motion in the shortest time. Once synchronized, the servo should hold its position rigidly at the correspondence point. Where the input order signal is continuously changing position, the servo must drive to the correspondence point in the same manner as with a fixed signal. Once in correspondence, the servo must drive at the same rate as the input order signal.

In a position control servo, the rate of movement is established by the rate of displacement. Hence there is a definite lag between the order signal position and the output position.

The accuracy of a servo is determined by its ability to measure and produce an error signal and to amplify the error signal to a level which will move the load to eliminate the error. Hence the overall accuracy of a servo is determined by the accuracy of its components and their input data.

The error detector receives and compares the ordered position and the actual position of the servo's output. Any error in the input data will naturally reduce the accuracy of the error detector's output. The accuracy of the error detector is determined by the amount of difference between its inputs that is necessary to produce a usable error signal.

The gain of the servoamplifier determines how large the error signal must be before amplifier output is sufficient to drive the error reducer. The higher the gain, the more sensitive the amplifier and the more accurate the servo. The efficiency of the error reducer determines how large the control current must be before it will drive.

The accuracy of the data, error detector, servoamplifier, and error reducer determines the static error or dead space of the servo. The static error is the angular displacement between the input and output of the servo under static conditions, (synchronized to a fixed order signal). The static error under load is the angular lag between the input and output of the servo when the input signal is moving at a constant velocity. The static errors are sometimes called steady state errors.

We have taken a negative approach to accuracy to show that servos have inherent sources of errors. Because of the errors, the term "null voltage" is used rather than "zero voltage," when the servo is synchronized. But do not get the false impression of large errors; the accumulative error in most servosystems is small.

GAIN, PHASE, AND BALANCE ADJUSTMENTS

In many servosystems the gain of the amplifier can be varied by an adjustment. The gain adjustment governs the amplitude or amount of the signal voltage applied to the amplifier or one of its stages. Normally, the highest gain possible, with the servosystem possessing a satisfactory degree of stability, is the most desirable.

In a.c. servosystems another adjustment which can control the sensitivity of the system is the phase adjustment. The phase adjustment is used to shift the phase relationship between the signal voltage and a reference voltage. In an amplifier with phase shift control the grid signal is shifted in phase with reference to the plate voltage of a tube. The tube's firing point is delayed or advanced depending upon the phase shift of the grid signal. The phase shift can vary the firing time of the tube over the plate's entire positive alternation.

A phase control is included in some servosystems using a.c. motors. The two windings of the a.c. servomotor should be energized by a.c. voltages that are 90° apart. This phase adjustment is included in the system to compensate for any phase shift in the amplifier circuit. The adjustment may be located in the control amplifier, or, in the case of a split-phase motor, it may be in the uncontrolled winding.

Servosystems using push-pull amplifiers must be balanced so that when there is no signal input to the amplifier, its output will be zero, and the servomotor will stand still with no creep. The push-pull amplifier must ensure equal torque in both directions of the servomotor.

Gain, phase, and balance adjustments are often present in one amplifier. These adjustments tend to interact so that when one is changed the others may be affected. Thus, after making one adjustment it is good practice to check the other adjustments.

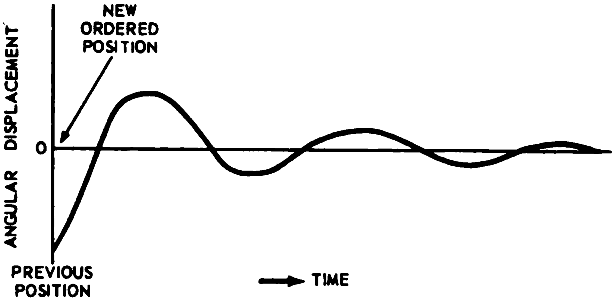
RESPONSE TIME

Servosystems should operate smoothly, rapidly, and with as few errors as possible. To obtain these operational characteristics, one quality is counterbalanced against the other. To increase the rapidity of response of the system to a signal, the gain is increased. This also tends to reduce error in the system. But a high gain or "tight" servo has a tendency to overshoot and oscillate, or, in other words, to be unstable. Response or synchronization time is the time the servo requires to settle down in synchronization to an order signal.

"HUNTING"

A servo will drive its load to the correspondence position. The servo's error signal and output torque are zero at correspondence, but due to the load's inertia it will continue to move. As the correspondence point is passed, the error signal tends to reverse the direction of movement. But a short time is needed to stop the load; and, during this time, the load will continue to move away from correspondence. When it does stop, the error signal will drive the load back towards correspondence. At correspondence the load has again acquired sufficient inertia to drive on past. The result is a series of overtravels of the correspondence point (fig. 4-33).

This condition is called "hunting", and is a characteristic which must be corrected in all servos. Obviously, hunting reduces the smoothness of the servo's followup action and increases its synchronization time. To overcome hunting, the servo must anticipate the load's inertia and



12.290
Figure 4-33.—Overtravels of the correspondence point.

its position with respect to the correspondence point.

When a servo is hunting, its oscillations about the correspondence are of a low frequency. A servo with a high gain amplifier has a tendency to oscillate at a high frequency with a low amplitude. The high frequency oscillations are started by some type of disturbance or variation such as random noise in the electrical section of the servo or lost motion in the mechanical section. Once the oscillations are started, the high gain of the amplifier tends to assist them while the inertia of the load continues to reintroduce the error caused by the oscillation.

STABILIZATION

To obtain smoothness of operation, the system's gain is damped. Damping can be obtained by either introducing a voltage in opposition to the signal voltage or placing a physical restraint on the servo output. The function of damping is to reduce the amplitude and duration of the oscillations that may exist in the system. Every system has one or more natural oscillating frequencies which depend on the weight of the load, designed speed, and other characteristics.

The degree of damping is determined by the required operating characteristics of the servosystem. If the system is OVERDAMPED, it will not oscillate about the correspondence point. However, due to the large amount of restraint placed on the servo, it will have a comparatively large dead-space or steady-state error. The overdamped servo will also take an excessively long time to synchronize (fig. 4-34).

On the other hand, the UNDERDAMPED servosystem will have instant response to an error signal. But it will have erratic operation due to the low amount of restaining force placed on the servo, and will oscillate about the point of synchronism. Somewhere between these two extremes, we can obtain adequate accuracy and smoothness plus a moderately short synchronizing time.

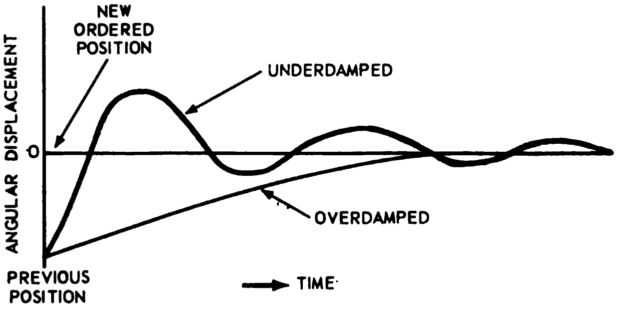


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Figure 4-34.—Degree of damping.

Viscous Damping

The simplest form of damping is viscous damping. This is the application of friction to the output shaft or load that is proportional to the output velocity. The amount of friction applied to the system is critical, and will materially affect the results of the system. The application of friction absorbs power from the motor, and this power is dissipated in the form of heat.

A pure viscous damper would absorb an excessive amount of power from the system. However, a system having some of the characteristics of a viscous damper, but with somewhat less power loss, is used in actual practice. The first damper of this type to be discussed utilizes a friction clutch to couple a weighted flywheel to the output drive shaft. A flywheel has the property of inertia.

FRICTION CLUTCH.—As the servomotor rotates, the clutch will couple a definite amount of this motion to the flywheel. The flywheel will gradually overcome its inertia and gain speed until it approaches the velocity of the motor. The flywheel in turning absorbs energy (power) from the servomotor. The amount of energy stored in the flywheel is determined by its velocity. Because of inertia, the flywheel will resist any attempt to change its velocity.

As the point of correspondence is neared and the error signal is reduced, the motor starts to slow down. The flywheel immediately releases some of its energy into the output shaft in an attempt to continue at the same speed. Thus the flywheel will cause a large first overtravel. The servosystem, to correct for this overtravel, reverses the direction of the motor. Once again the flywheel resists the motor movement and absorbs energy from the system. This drastically reduces the second overtravel and all subsequent overtravels of the motor. This effect dampens the oscillations about the point of correspondence and reduces the servosystem's synchronizing time.

The motor rotation is transmitted to the flywheel through the friction clutch. The inertia of the flywheel is an additional load on the motor. The friction clutch will slip with any rapid change of direction or speed. This slipping effectively disconnects the flywheel instantaneously and thus governs the amount of power the flywheel will draw from the line.

MAGNETIC CLUTCH.—Another type of viscous damper is the MAGNETIC or EDDY CURRENT damper. The magnetic damper is functionally similar to the friction clutch damper. The principal difference between the two is in the method of coupling the flywheel (inertia weight) to the servomotor output shaft. In the magnetic damper, the shaft and flywheel are coupled by a magnetic field, rather than a frictional contact. The coupling is made by the interaction of a magnetic field generated by a permanent magnet which rotates with the rotor of the servomotor and the induced eddy current in the flywheel.

The effect of viscous damping is shown in figure 4-35. The solid line shows the action of the load without damping. The time required to reach a steady-state condition should be noted. This time is greatly reduced with damping, although the initial overshoot is increased. Viscous dampers effectively reduce transient oscillations, but they also produce an undesirable steady-state error (velocity lag or position error). Since the friction damper absorbs power from the system, its use is normally limited to small servomechanisms.

Error-Rate Damping

Since no physical device can respond instantaneously to a sudden force, there is a time lag between the signal input of a servosystem and its output response. To reduce this time lag, amplification is increased. We know that this also accentuates the tendency of the system toward instability. Viscous dampers act as part of the servo load, so they are not the answers to reducing the response lag. The answer lies in increased amplification with error-rate damping.

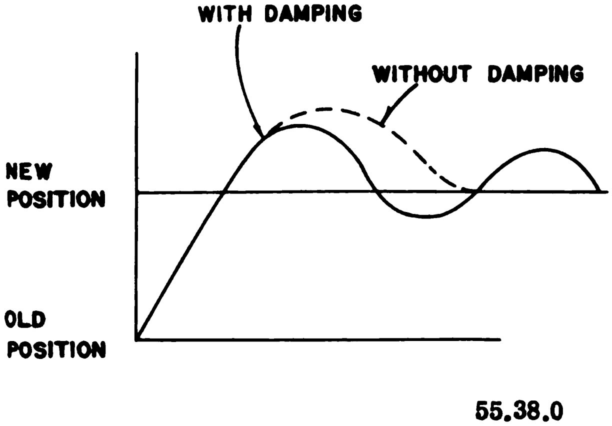

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Figure 4-35.—Effect of friction damper.

Error-rate damping consists of introducing a voltage that is proportional to the rate of change of the error signal. This voltage is combined with the error signal in the proper ratio to obtain optimum servo operation with negligible overshooting and oscillations.

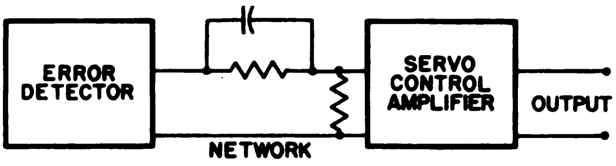
The advantages of error-rate damping are:

1. Maximum damping occurs when a maximum rate of change of error signal is present. This normally would occur when the servo load reverses direction. Obviously, this is when maximum damping action is required.
2. Since a CHANGE in the signal causes damping, there is a minimum amount of damping when no signal, or a signal of constant strength, is present. This means small steady-state errors.

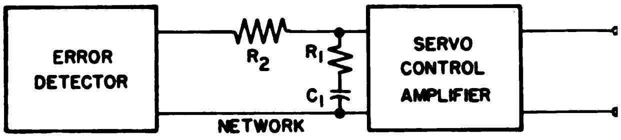
Error-rate voltages are generated by either electromechanical devices or electrical networks. An electromechanical device widely used to generate an error-rate voltage is the tachometer or rate generator, commonly called a "tach", as discussed in chapter 1. The tach is mechanically coupled to, and rotates with, the servo's output shaft. Its output voltage is proportional to the output velocity of the servo. Since the voltage output is proportional to load velocity it is also proportional to the inertia of the load due to its velocity. Hence the output voltage can be fed back to the amplifier to indicate the load's velocity and therefore its inertia.

ELECTRICAL ERROR-RATE VOLTAGE NETWORKS.—Electrical networks used for error-rate damping consist of a combination of resistors and capacitors forming an RC differentiating network. From your study of basic electricity, you know that a differentiating circuit produces an output voltage that is proportional to the rate of change of the input voltage. In an RC circuit, if the voltage across the resistor is used as the output, it is referred to as a DIFFERENTIATOR (fig. 4-36), and, if the voltage across the capacitor is the output, it is referred to as an INTEGRATOR (fig. 4-37).

Consider the integrator circuit shown in figure 4-37—or, as it is sometimes called, an integral control—to explain error-rate damp-



55.41
Figure 4-36.—Error-rate stabilization network.



55.4
Figure 4-37.—Integrator used as an integra stabilization network.

ing. The integral control circuit is shown in its simplest form. It is made up of a combination of two resistors and a capacitor. Notice that the network is in series with the error detector and the amplifier. The circuit is designed for d.c. signals; if the error detector puts out an a.c. signal, it must be demodulated before it enters the network. The signal is dropped across R2 and the R1, C1 leg of the network. The R1, C1 leg is in parallel with the amplifier's input circuit. Therefore, only that portion of the signal developed across the R1, C1 leg is fed into the amplifier. R2 is in series with the leg and is larger than R1. Briefly, here is how the circuit works.

Assume that the error signal is steady or changing slowly. Initially, all of the constant error voltage is divided between R1 and R2. But the longer the error voltage is applied, the more C1 charges up. The increasing voltage drop across C1 adds to the drop across R1. Since these two components are in parallel with the amplifier, their combined voltages will appear at the input terminals of the amplifier. In effect, the servo will overcorrect the error signal and the output shaft will catch up with the input signal. As the drive increases its velocity it will reduce the error signal. The capacitor C1 will start to discharge and oppose the reduction. The damping action of the capacitor's charging and discharging voltages, which oppose the changes in the error signal, will assist the servo to settle down quickly at the new velocity.

CHAPTER 5

GYROS AND ACCELEROMETERS

This chapter discusses the fundamental prin-iples of gyroscopes and describes how they are dapted for use in various shipboard and aircraft pplications. The chapter also presents a brief iscussion on the basic principles of acceler-meters and describers some of the common ypes of accelerometers used in the Navy.

THE GYROSCOPE

The gyroscope, commonly called a gyro, has existed since the first electron was sent spinning on its axis. Electrons spin and show all the characteristics of a gyro, and so does the earth which spins about its polar axis at over 1000 miles per hour at the Equator. The earth's rotation about its axis has provided the stabilizing effect that has kept the North pole pointed within 1° of Polaris (the North star) probably since the beginning of time.

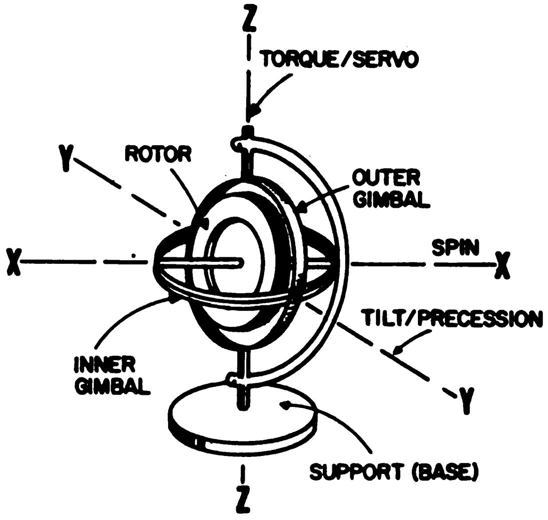
Any rapidly spinning object—a top, wheel, an airplane propeller, or a spinning projectile—is fundamentally a gyroscope. Strictly speaking, however, a free gyroscope may be defined as a mechanical device containing a spinning mass which is universally mounted, that is, mounted so it can assume any position in space. Figure 5-1 shows a basic free gyro. As you can see, a heavy wheel (rotor) is mounted so that its spin axis is free to turn in any direction. The wheel can spin about axis x, it can turn about axis y, and finally turn about axis z. With this mechanical arrangement the spinning wheel can assume any position in space.

The major components of the free gyro (fig. 5-1) are the rotor, inner gimbal, outer gimbal, and base or support. The three major axes of any gyro are the spin, torque or servo, and precession. The spin axis is, of course, the axis on which the rotor spins. The torque or servo axis is the axis about which the disturbing force is applied. The precession or tilt axis is the axis the gyro turns about as a result of the force applied to the torque axis.

There are several ways of naming the axes of a gyro. The name assigned an axis is usually taken from the reference line or plane it has established. Some of the names are: north-south, east-west; vertical, horizontal; roll, pitch; level, crosslevel; input, output; torque, sensitive.

The term gimbal may be defined as a device for permitting a body to incline freely in any direction and retain that position when the support is tipped or repositioned. When the rotor of the free gyro is spinning, the support may be moved about all three axes without the rotor position being disturbed.

Gravity is a force that acts along parallel lines upon each particle of matter that makes up the gyro. Each force acts independently of all other forces, but force is a vector quantity



12.138
Figure 5-1.—Basic free gyro.

having both a direction and a magnitude. Therefore, we can plot a resultant of the forces of gravity acting on the gyro. The magnitude of this single force is exactly equivalent to the separate parallel forces. Its point of application is called the center of gravity. In order to have a balanced gyro the center of gravity must be located at the intersection of the three axes of the gyro. This must be true when the gyro is not spinning, for a static balance; and when it is spinning, for a dynamic balance.

A gyro can have two different degrees of freedom, depending upon the number of gimbals in which it is supported and the way the gimbals are arranged. You must not confuse the term "degrees of freedom" with an angular value such as degrees of a circle. The term as it is applied to gyros is an indication of the number of axes about which the rotor is free to precess. (Some texts consider the spin of the rotor as one degree of freedom but most do not.)

A gyro mounted in two gimbals (as in fig. 5-1) usually has 2 degrees of freedom. When two gimbals are employed it is said to be universally mounted, or a free gyro.

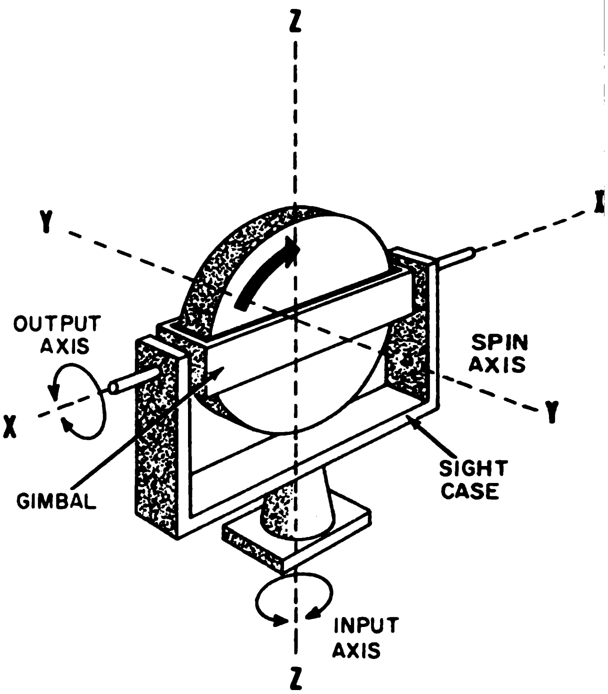
A gyro mounted in ONE GIMBAL usually has one degree of freedom. A gyro wheel is mounted in a gimbal and spins in the Y-Y axis, (fig. 5-2). When the wheel is spinning it has rigidity in the Y-Y spin axis and will resist an attempt to change its plane of rotation. The gimbal is supported in the two arms of the mounting frame, and can pivot about the X-X output axis. The X-X axis is the only one in which the gyro can precess. In all other directions there is a fixed mechanical coupling between the gyro and its mounting. The mounting frame can be rotated about the Z-Z axis.

The single degree of freedom gyro is sometimes referred to as a restrained gyro.

When the rotor of a gyro is spinning, the gyro develops two fundamental properties that it does not have when the rotor is at rest. These properties are RIGIDITY and PRECESSION.

RIGIDITY

A gyro is a spinning body that tends to keep its spin axis rigidly pointed in a fixed direction in space. The idea of maintaining a fixed direction in space is easy to show. When any object is spinning rapidly, it tends to keep its axis pointed always in the same direction. A toy top is a good example. As long as it's spinning fast, it stays balanced on its point. Because of its rigidity it resists the tendency of gravity to change the direction of its axis. You can think of many more examples.

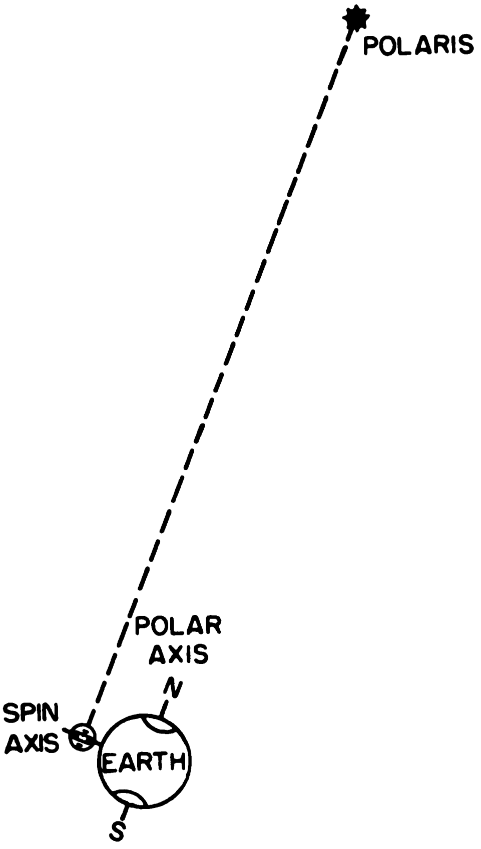


12.152.1
Figure 5-2.—Single degree of freedom gyro.

A fixed direction on earth is by no means fixed in space, because the earth turns once on its axis every 24 hours. It makes a complete revolution around the sun every year. And the sun itself is moving, taking the earth and the other planets with it. Because of these motions, the expression "fixed direction in space" as used here is theoretical. If that were an exact statement, our universe would have to be unaccelerated and therefore nonrotating. But for all practical purposes we can say this: A line from the earth to a distant star is a fixed direction in space (fig. 5-3). If the spin axis of a spinning gyro is pointed at a distant star, it will remain on the star as long as no external torque is applied to the gyro.

Any rapidly spinning body has the property of rigidity. A wheel spinning on its axis is in effect a gyro and offers resistance to any attempt to tilt it from whatever position it has assumed in space.

The gyro rotor is not rigid as we think of rigidity in terms of a building or a tree. It can be moved in several ways. That is to say, it can



12.140

igure 5-3.—A gyro on the earth pointing in a fixed direction in space.

e moved freely from one place to another with e gyro offering little or no resistance so long s the movement is parallel to or perpendicular the plane of the spin axis. This is called ranslation. In translation no attempt is made to hange the spin axis. On the other hand, when we ave a rotor spinning on an axis and we try to lt it, it offers resistance, and this resistance is proportion to the effective weight of the spinning ody and the speed at which it is spinning.

Three factors determine a gyro's rigidity, or e strength with which it resists any external orce tending to displace its rotor spin axis. hese factors are the weight of the rotor, the istribution of the weight, and the rotor speed.

We can consider the gyro as an enclosed echanical system. The energy in the system is qual to the input energy. Hence the energy ecessary to spin the gyro rotor is contained the rotor as angular momentum. Momentum s the energy in a body due to its velocity. The heavier the gyro rotor, the larger the torque necessary to spin it, and the greater the angular momentum of the rotor. If we have two rotors with identical shapes but of different weights spinning at the same velocity, the heavier of the two will be more rigid in its spin axis since it contains the greater angular momentum and, as will be explained next, the greater inertia.

To understand the effect of weight distribution in a rotor of a gyro, consider two rotors of the same weight, with the diameter of one, half that of the other. Now, when we spin both of these rotors at the same speed, we find that the rotor with the greater diameter is much more rigid than the one with the smaller diameter. Next we find that we can make both rotors equally rigid by causing the rotor with the smaller diameter to spin faster than the larger rotor. Thus rigidity is dependent upon both speed and distribution of weight. The weight of the larger rotor being farther away from the axis of spin causes it to be more effective for rigidity. In physics it is said that the weight of the larger diameter rotor has the greater "moment of inertia."

INERTIA is a fundamental property of matter. Nothing in nature will start or stop moving by itself. Some external force must be applied to it first. For example, you have felt the tendency to fall backwards while standing in a bus which started suddenly. What happened was that your body tended to remain stationary but your feet were carried forward with the moving bus. From this experience you can come to the conclusion that when a body is at rest it will tend to remain at rest. After you regained your balance and your body started moving at the same speed and direction as the bus, everything was fine. Fine that is until the driver suddenly stopped the bus. Again you lost balance and tended to fall forward. In this case your body tried to continue in the direction in which the bus was traveling, but your feet were retarded by the stopping bus. From this experience we can conclude that a body in motion will tend to follow in the same straight line or direction unless acted upon by some external force. The two experiences mentioned are examples of Sir Isaac Newton's first law of motion which states: A body at rest remains at rest, and a body in motion continues to move at a constant speed along a straight line, unless the body is acted upon in either case by an unbalanced external force. Newton's first law of motion applies equally well to rotating bodies. Consider for a moment the spinning rotor of a gyro.

Every particle of matter in the gyro rotor is trying to move in a straight line; but the circular structure of the wheel prevents this, and pulls them all into a circular path. The particles keep trying, nevertheless, to stay in as straight a line as possible. Consequently the rotor keeps rotating in the same plane unless acted upon by some outside force. If no external forces are present, the wheel will not move from its plane of rotation. Common sense tells us that if this is so, the spin axis must remain fixed.

Moment of inertia is a measure of the torque needed to bring about a change in the motion of a rotating body. Moment is defined as the tendency of energy acting on a body to produce motion, while inertia is the tendency of a body to resist a change in motion.

MOMENT OF INERTIA can be demonstrated with two weights—one heavy and the other light, a board, and a fulcrum, arranged in the manner of a seesaw. To balance the two weights, we have to place the heavy weight near the center and the light weight near the end of the board. This makes the light weight more effective by being farther out from the fulcrum and having greater leverage. If we have two equal weights, we can make one outbalance the other by putting one farther out on the board. The same principle applies to two rotors of equal weight, the rotor having its weight distributed "farther out on the board" has the greater moment of inertia. Its weight is more effectively placed and makes the wheel more rigid in space.

Now we can conclude that a gyro resists any tilting force, and that the amount of resistance depends upon the weight, distribution of the weight, and the speed of the rotor. If we were to design a gyro for maximum resistance to an external force we would make it as heavy as possible, put as much weight as far as possible from the center of rotation, and spin the gyro wheel as fast as possible. As long as the gyro and gimbal bearings were frictionless and the center of gravity of the wheel was at the intersection of the three major axes, no displacement of the support of our perfect gyro could change the position of its rotor in respect to space. This property of a gyro is commonly called rigidity. It is also sometimes referred to by other names such as "rigidity in space," "rigidity of plane of rotation," "gyroscopic inertia," and "gyroscopic stability."

A spinning gyro mounted in an aircraft demonstrates the property of rigidity as shown in figure 5-4.

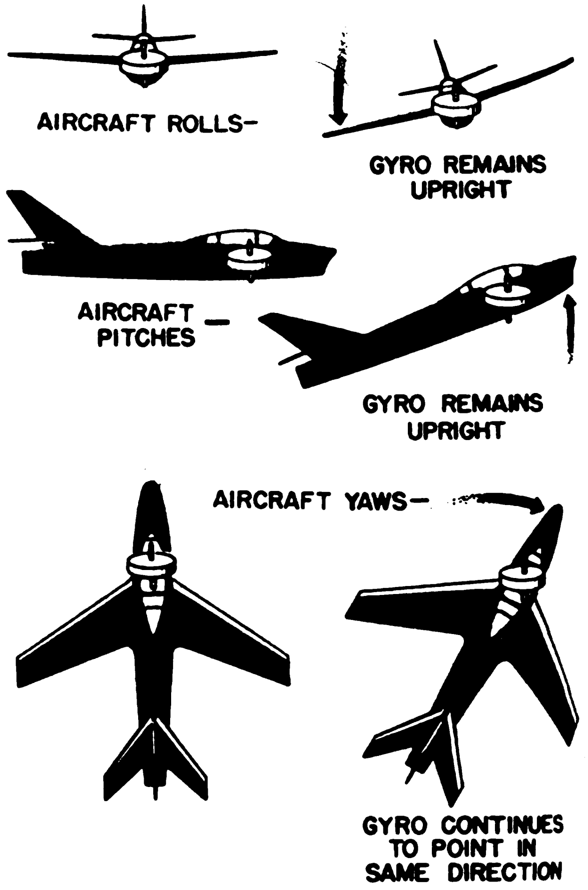


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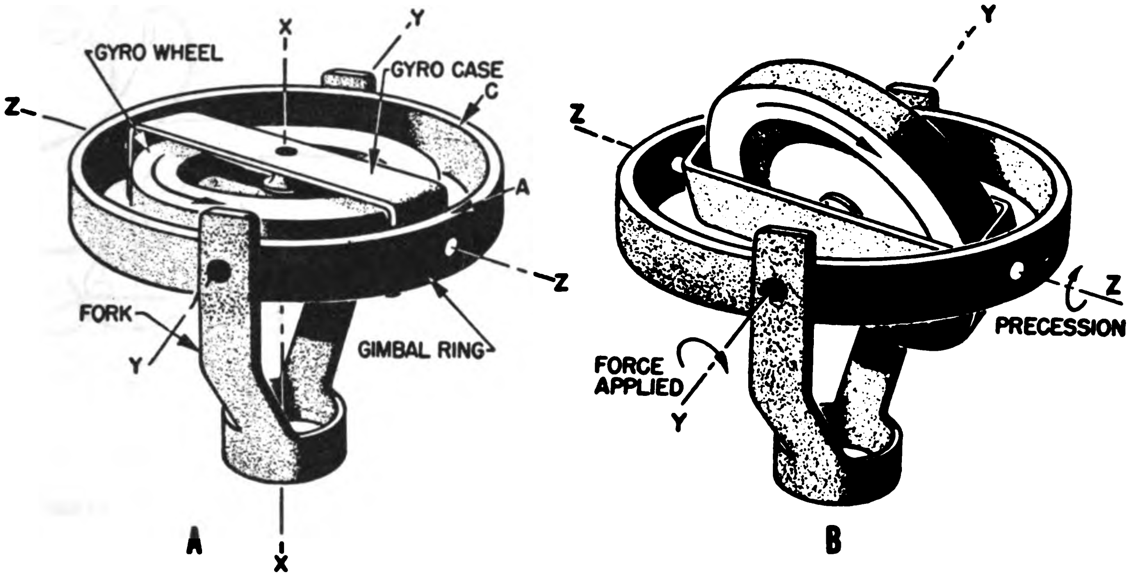
Figure 5-4.—Aircraft reference and gyro rigidity.

PRECESSION

Precession may be defined as the resultant movement of a spinning mass when a force is applied that attempts to change the spin axis. Precession takes place whenever any force tends to tilt the axle of a spinning gyro. The precession caused by this force is always about an axis at right angles to the axis about which the force is applied.

To show the effect of precession, push down on the gimbal ring at point A at the nearer end of the z-z axis (fig. 5-5A). You would expect the ring to tilt around the y-y axis. Instead of rotating about the y-y axis as you might expect, however, the gyro case will turn about the z-z



12.141
Figure 5-5.—Gyro action.

ds. You can see the effect of precession in gure 5-5B.

Similarly, going back to figure 5-5A, sup- se you push sideways on the top of the x-x ds (the spinning axle of the gyro), trying to tate the wheel around the z-z axis. Then, stead of rotating about the z-z axis, the gim- l ring will turn around the y-y axis.

If you push down at point C on the gimbal ng (fig. 5-5A) midway between the y-y and -z axes, you will find that the gimbal ring ro- tes around the y-y axis, and that the gyro se rotates around the z-z axis. The total fect causes the gyro wheel to turn around a ne lying from point C through the center of e gyro wheel.

Here's a rule that applies to all spinning yros: THE GYRO WILL ALWAYS PRECESS T RIGHT ANGLES TO THE DIRECTION OF HE APPLIED FORCE.

Look at figure 5-5A again. If you keep push- g down on the gimbal ring at point A, the yro case will keep turning until the axle of the yro wheel is horizontal. Then there will be no urther precession. At this point the gyro wheel spinning in the same direction in which the pplied force is pushing.

Here's another rule: A GYRO ALWAYS PRE- ESSES IN A DIRECTION TENDING TO LINE SELF UP SO THAT ITS ROTOR SPINS IN THE SAME DIRECTION THAT THE APPLIED FORCE IS TRYING TO TURN IT. In other words, the spin axis chases the torque axis. When the two come into coincidence, precession no longer takes place.

Any force that tends to change the plane of rotation causes a gyroscope to precess. Precession continues as long as there is a component of force acting to change the plane of rotation and precession ceases immediately when the force is removed. If the plane through which the force is acting remains unchanged, the gyroscope precesses until the plane of the rotor is in the plane of the force. When this position is reached, the force is about the spinning axis and can cause no further precession.

If the plane in which the force acts moves at the same rate and in the same direction as the precession which it causes, the precession will be continuous.

A valid explanation of why precession occurs requires the use of vector representations of torques and angular motions and is beyond the scope of this text. However, the concept of torque should be understood since that term is used extensively in the discussion of gyros. Torque is defined as the product of a force which tends to produce rotation and the perpendicular distance from the line in which that force is acting to the axis about which the rotation tends to occur.

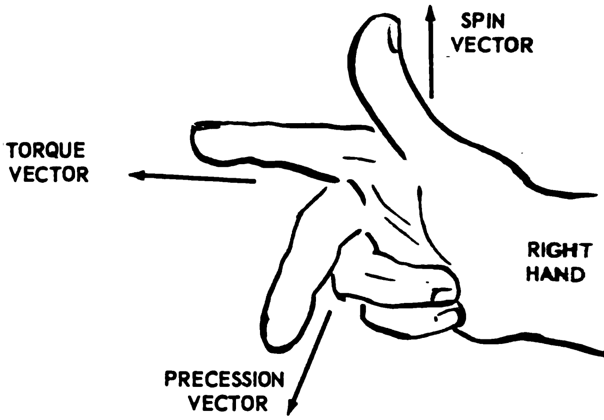
Whereas force acts in a straight line at or on a point, torque occurs in a plane, and is referred to as being applied about an axis. A force acting on the axle of a gyroscope produces a torque about either or both of the gyro's other two axes. For a given amount of force, the greater its distance from the axis of rotation, the greater the torque. If the force is acting on the axis of rotation, the torque is zero.

Any force operating through the center of gravity of the gyroscope does not change the angle of the plane of rotation but moves the gyroscope as a unit without changing its position in space. Such a force operating through the center of gravity is known as a force of translation. Thus, the spinning gyroscope may be moved freely in space by means of its supporting frame, without disturbing the plane of rotation of the rotor. This condition exists because the force that is applied through the supporting frame acts through the center of gravity of the rotor and is a force of translation. It produces no torque on the gyro rotor.

For a given force, the rate of precession is governed by the weight, shape, and speed of the wheel. These factors are the same as those that determine the rigidity of a gyroscope. Therefore, it is reasonable to assume that there is a relationship between the rigidity of a gyroscope and the rate at which a given force will cause it to precess. Such a relationship does exist. The greater the rigidity of the gyroscope, the more difficult it is to cause precession, and the less the precession for a given force will be. The amount of gyro precession is determined by the strength of the precessional force, the time the force is acting, and the gyro's resistance to the force.

A convenient rule for determining the direction of precession is by the use of the fingers of the right hand. This method is not new since a similar means is used to demonstrate the motion of a conductor in a magnetic field, as described in Basic Electricity, NavPers 10086-B.

The three vectors previously mentioned may be represented by arranging the thumb, index finger, and middle finger of the right hand mutually perpendicular as shown in figure 5-6. The thumb points in the direction of the spin vector, the middle finger points in the direction of the precession vector, and the index finger points in the direction of the torque vector. These vectors can be considered as the axes about which angular motion takes place. All rotary motions are clockwise as indicated in the figure when viewing in the direction that the finger and thumb are pointing.



12.143

Figure 5-6.—Right-hand rule for precession.

The hand rule is useful for analyzing an gyroscope motion problem. If the direction o any two of the three vectors are known, th direction of the third vector can be found an the motion around this vector may be determined

Still another use of the hand rule is in determining the direction of the spin vector (fig 5-7). By curving the fingers of the right han around the gyro in the direction the rotor i turning, the thumb will then point in the direction of the spin vector. Also the direction o the torque vector may be found by wrappin the fingers in the direction of the applied torqu (the direction the gyro would rotate if the roto were not spinning); the thumb points in th direction of the torque vector.

EFFECT OF EARTH'S ROTATION

A free gyro (not provided with an erectio or leveling system) maintains its spin axi fixed in relation to space, and not in relatio to the surface of the earth. For example, imagin such a gyro at the Equator, its starting positio being with the spin axis horizontal and pointe in an east-west direction (fig. 5-8). The eart turns in the direction of the arrow, or clockwise, with an angular velocity of one revolutio every 24 hours. To an observer out in space, the spin axis would appear to maintain it direction pointing east.

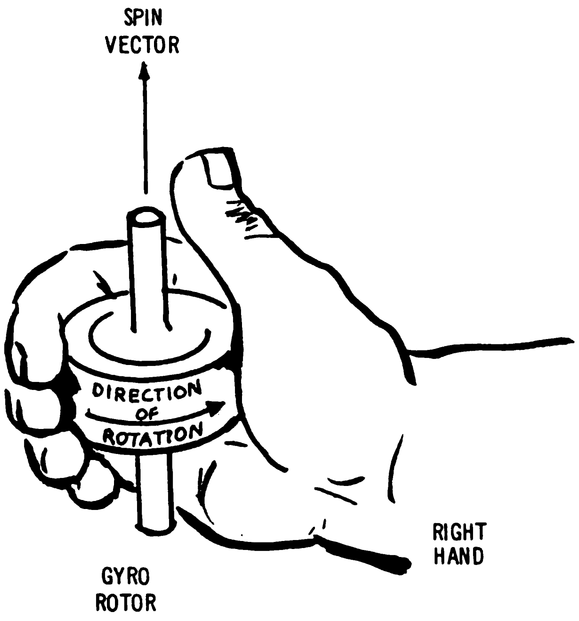


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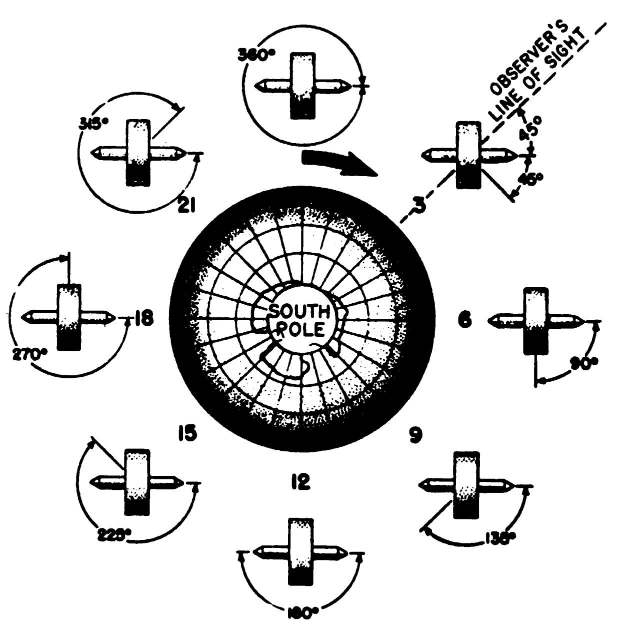
Figure 5-7.—Determining spin vector direction.



175.36
Figure 5-8.—Free gyro at the equator viewed from outer space.

However, to an observer on the earth, the spin axis appears gradually to tilt or drift fig. 5-9). At the end of 3 hours the spin axis has tilted 45°; at the end of 6 hours, the spin axis has tilted 90° and is in a vertical position. At the end of 12 hours the spin axis is again horizontal but pointing west; at the end of 24 hours it s back where it started. This APPARENT ROTATION (also called apparent precession and apparent drift) creates the illustion that the gryo has turned over end-for-end, and a complete revolution is made every 24 hours as shown in igure 5-9. Actually however, the gyro has maintained its position in space and the earth has turned around it.

The apparent rotation or tilt of the gyro horizontal axis is sometimes referred to as horizontal earth rate effect. This effect varies with the cosine of the latitude, and is maximum at the equator and zero at the poles.

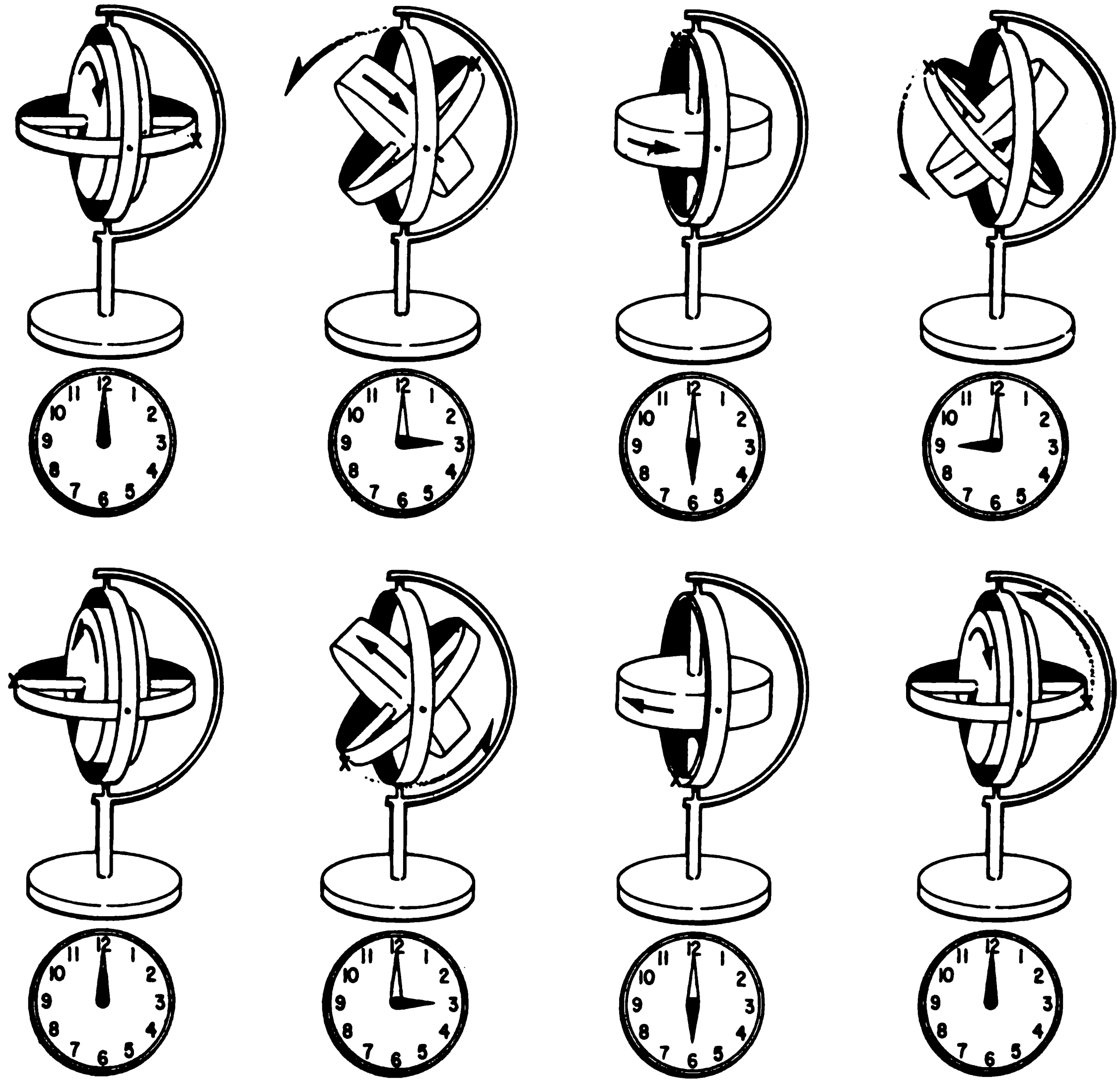
Now assume that the spinning gyroscope, with its spinning axis horizontal, is moved to the North Pole (fig. 5-10). To an observer on the earth's surface the gyroscope appears to rotate about its vertical axis. To an observer in space the gyroscope axle appears to remain fixed and the earth appears to rotate under it. This apparent rotation about the vertical axis is referred to as vertical earth rate effect, and varies with the sine of the latitude. It is maximum at the poles and zero at the equator.

When the gyroscope axle is placed parallel to the earth's axis at any location on the earth's surface, the apparent rotation is about the axle of the gyroscope and cannot be observed. At any point between the equator and either pole, a gyroscope whose spinning axis is not parallel to the earth's spinning axis has an apparent rotation that is a combaination of horizontal earth rate and vertical earth rate.

Apparent rotation of a gyro makes it unfit for use as a reference over an extended period of time unless some sort of compensating or erecting mechanism is used to keep the gyro in a fixed position relative to the earth's surface. Over a relatively short period of time, however, the gyro can be used to establish a satisfactory reference without the need for a compensating system.

EFFECT OF MECHANICAL DRIFT

A directional error in a gyro is produced by random inaccuracies caused by mechanical



175.37

Figure 5-9.—Free gyro at the Equator viewed from the earth.

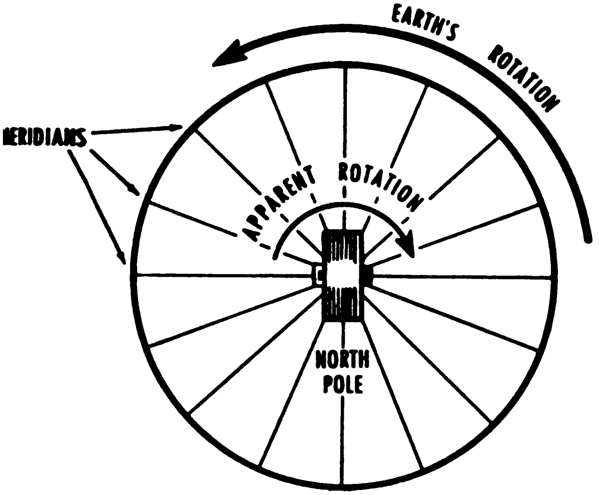
drift and the effect of the earth's rotation (apparent drift).

There are three general sources of mechanical drift:

1. Unbalance. A gyro often becomes dynamically unbalanced when operated at a speed or temperature other than that for which it was designed. The static balance of the gyro is upset when its center of gravity is not at the intersection of the three major axes. Some unbalance of both types will exist in any gyro, since manufacturing precesses cannot produce a perfectly balanced gyro.

2. Bearing friction. Friction in the gimbal bearings results in loss of energy and incorrect gimbal positions. Friction in the rotor bearings causes mechanical drift only if the friction is not symmetrical. An even amount of friction all around in a rotor bearing results only in a change of the rate of rotation.

3. Inertia of gimbals. Energy is lost whenever a gimbal rotates because of the inertia of



77.198
Figure 5-10.—Apparent rotation of a gyro at the north pole.

the gimbal. The greater the mass of the gimbal, the greater the drift from this source.

The complete elimination of mechanical drift in gyros is impossible. However, by proper design it is kept to a minimum. Any error which still exists can be corrected for.

HORIZONTAL AND VERTICAL GYROS

A free gyro can detect motion about any axis but the spin axis. Thus gyros may be mounted with their spin axes horizontal or vertical depending upon their application. For example, a free gyro with its spin axis horizontal (fig. 5-1) mounted on a ship or aircraft could detect motion about the Z axis (heading). It could also detect motion about the Y axis if the ship or aircraft was on a true North-South or East-West heading (pitch on a North-South heading, and roll on an East-West heading). It could not, however, detect any motion about the X axis.

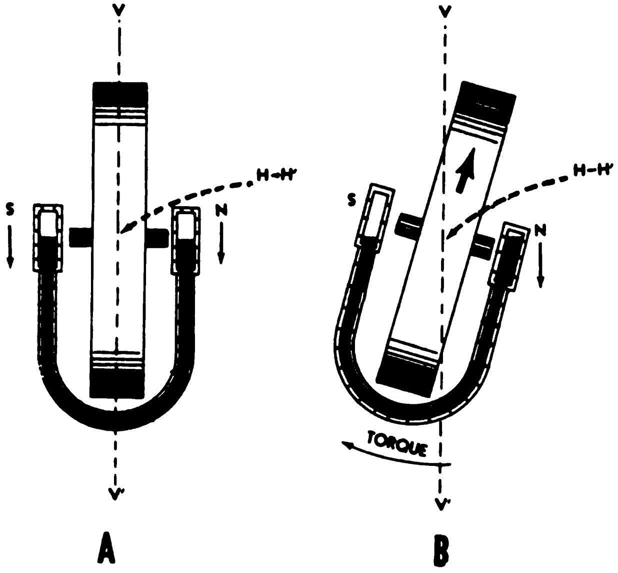
To accurately detect roll, pitch, and heading motions requires at least two gyros, a horizontal and a vertical gyro, or two horizontal gyros with their spin axes at right angles to each other.

To make a gyroscope into an accurate direction-indicating device, torques must be provided of the correct magnitude and in the proper direction so as to cause the gyro spin axis to assume the required direction after the rotor is up to speed. In addition, torques must also be provided to precess the gyro back to the required position so as to cancel the effects of the earth's rotation (apparent rotation) and mechanical drift. There are various methods used for providing these torques. Some of the more common ones are described in the following paragraphs.

MAINTAINING THE SPIN AXIS HORIZONTAL

If a free gyro is set with its spin axis aligned North-South and parallel to the earth's surface (level) it will remain in this position (provided there are no mechanical drift or other disturbing forces present) until the effect of the earth's rotation is sufficient to cause precession. A common method for maintaining the gyro axle level (and thus compensating for the tilting effect caused by the earth's rotation) utilizes the action of a mercury ballistic.

In its simplest form, the mercury ballistic consists of two mercury-containing reservoirs, one mounted at each end of the rotor axle. The two reservoirs are connected by a pipe so that the mercury is free to flow from one reservoir to the other, as shown in figure 5-11.

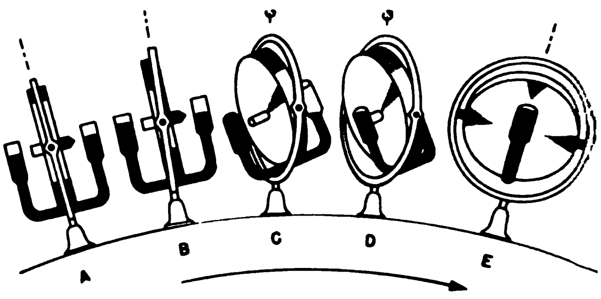


77.201
Figure 5-11.—Action of a mercury ballistic.

When the axle is level (fig. 5-11A), each reservoir contains the same amount of mercury, each weighs the same, and each exerts the same downward force on its end of the axle. Therefore, no torque is produced about any axis. When the axle is tilted, even slightly (fig. 5-11B), mercury runs through the connecting tube from the higher container to the lower container. The amount of mercury in the two tanks is no longer equal. The lower tank is heavier because it contains more mercury. Therefore, the lower tank exerts more force against its axle than does the upper tank, and produces a torque about axis H-H'. This torque, which seemingly tends to increase the tilt, instead, causes precession about the vertical axis, V-V'.

When the north end is low, the excess mercury in the north tank exerts a downward pressure on the north end of the axle and causes precession to the east, or clockwise. When the north end is high the excess mercury in the south tank exerts a downward pressure on the south end of the axle and causes precession to the west, or counterclockwise. When the north end of the rotor axle is east of the meridian (North), the earth's rotation causes it to rise. When a mercury ballistic is added to the gyroscope, the elevation of the north axle produces a torque about the horizontal axis that causes counterclockwise, or westerly, precession. When the north end of the axle is west of the meridian, the earth's rotation causes it to drop. A low north axle causes the mercury ballistic to exert a torque about the horizontal axis that gives clockwise, or easterly, precession.

If this gyroscope with its mercury ballistic is set on the equator with the axle pointing to the east of the meridian and with the rotor spinning counterclockwise (fig. 5-12A) the north end of the axle tilts upward because the earth rotates under it. When this tilt occurs mercury flows from the north to the south tank, and the south tank becomes the heavier. The south tank applies a torque around the horizontal axis (fig. 5-12B). This torque results in a precessional motion around the vertical axis toward the meridian and the west. Because the earth is constantly turning, the gyroscope continues to tilt upward, more mercury flows to the south tank, and the torque around the horizontal axis gradually increases with a corresponding increase in the precession about the vertical axis (fig. 5-12C&D). This upward tilting continues until the gyroscope axle is on the meridian (fig. 5-12E). The south tank contains more mercury than the north tank, and the gyroscope is tilted upward its greatest amount. At this point the rate of precession is at its peak.



77.20

Figure 5-12.—Gyro with mercury ballistic at th equator.

After the gyroscope axle crosses the meridian it begins tilting downward so that mercury flows from the south tank to the north tank. This transfer of mercury gradually reduces the torque about the south end of the axle with a corresponding gradual reduction in the rate of precession of the gyroscope about the vertical axis. When the gyroscope axle is once more level, it points to the west of the meridian, the mercury is distributed equally in both tanks, no torque is applied to either the north axle or the south axle, and precession ceases.

As the earth continues moving, the north end of the gyroscope axle tilts downward, and mercury flows into the north tank, which applies a torque to the north end of the spin axis. Hence the direction of precession is reversed and is now toward the east. The downward tilt of the spinning axis continues, and the torque and rate of precession increase. By the time the gyroscope axle reaches the meridian, it has attained its maximum rate of precession again, but it now has a downward tilt. After the gyroscope passes the meridian, the rotation of the earth starts the north end of the gyroscope axle tilting upward. As this action occurs the torque about the north axle gradually diminishes to zero and the precessional motion around the vertical axis slows down until the gyroscope axle is once more horizontal and precession ceases. When the gyroscope axle becomes horizontal, the axle points in its original starting position.

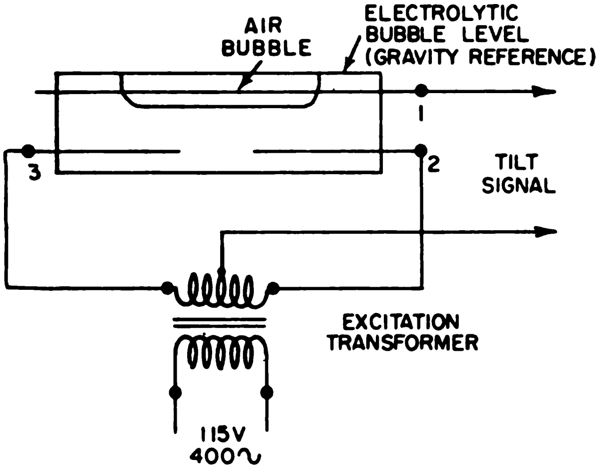
Thus the mercury ballistic causes the gyroscope to continuously seek a level position with its axle aligned North-South. This is called

aking the gyroscope "north seeking" in gyro-
mpass texts. The north end of the gyro axle
es not continuously point North as a result
the action of the mercury ballistic, but oscil-
tes in an elliptical path back and forth across
e meridian. These oscillations are dampened
it to make the gyroscope into a gyrocompass
discussed in the next chapter.

An electronic type of gyro leveling system
es as electrolytic bubble level which generates
signal voltage proportional to the tilt of the
ro axle. This signal voltage is amplified and
d to the control field of an electromagnetic
rquer which provides the proper torque to
recess the gyro back to level.

The electrolytic bubble level is mounted on
e gyro so that it is parallel to the gyro spin
cis. It is a cylindrical glass vial containing
ree platinum electrodes, the vial being nearly
lled with an electrolyte so that a bubble is
rmed at the top of the vial as shown in figure
-13.

When the vial is horizontal (indicating that
e gyro is level), the bubble is centered, and
e resistance between the top electrode and
ither lower electrode is equal. If the vial tilts
o that the bubble moves to the left, there is
ss electrolyte between the top electrode and
he lower left electrode and consequently the
esistance between the two is increased. The
esistance between the top and lower right electrode is correspondingly decreased, the difference in resistance being proportional to the movement of the bubble.



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igure 5-13.— Electrolytic bubble level, simplified schematic diagram.

The two lower electrodes are excited from the opposite ends of the output winding of the excitation transformer. The tilt signal output from the electrolytic bubble level is obtained between an accurately determined center-tap (signal common) of the excitation transformer secondary and the top electrode. When the level is horizontal, the voltage between the top electrode and either lower electrode are equal and opposite and the tilt signal output is zero. When the level is tilted from the horizontal, an output signal voltage will be produced which is proportional in magnitude to the amount of tilt and and with the phase or instantaneous polarity of the voltage dependent upon the direction of tilt.

Another type of electronic leveling system uses two photoelectric (PE) cells, an exciter light, and a shutter that moves between the PE cells and the exciter light. The arrangement is such that when the gyro axle is level, the shutter permits equal amounts of light to fall on each PE cell resulting in equal but opposite voltage outputs. If the gyro axle tilts, however, the PE cells receive unequal amounts of light and produce unequal voltage outputs. Thus the resultant voltage output from the PE cells corresponds to both the magnitude and direction of the gyro tilt. This voltage is used to supply a torquer which provides the necessary torque to level the gyro similar to the electrolytic bubble level system.

As stated previously, the horizontal gyro at any location on the earth's surface other than the equator appears to turn about its vertical axis in addition to tilting about its horizontal axis. This effect must also be compensated for in certain applications where the gyro is used as a continuous direction-indicating device. This type of compensation is sometimes referred to as latitude correction and is accomplished in many ways by both mechanical and electronic methods. All methods accomplish the same result. They provide the necessary forces or torques which cause the gyro to precess at the proper rate and in the proper direction so as to cancel the effects of the earth's rotation.

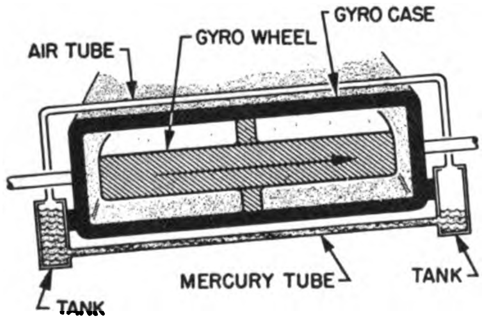
MAINTAINING THE SPIN AXIS VERTICAL

In the vertical gyro, the spin axis must be maintained perpendicular to the earth's surface. This means that the gyro wheel must be kept in a horizontal plane parallel to the earth's surface. To accomplish this, an erection system is used.

A common type of erection system similar to the mercury ballistic described earlier is shown in figure 5-14. This system consists of two tanks of mercury fastened to opposite sides of the gyro case and connected by a small mercury tube. A small air tube is also connected between the tanks to prevent the forming of a vacuum. If the gyro tilts away from the reference, the mercury will flow from one tank to the other. The added weight will provide a torque which causes the gyro to precess. At this point if you apply the rule for precession, you will see that the precession would be 90 degrees away from the desired direction.

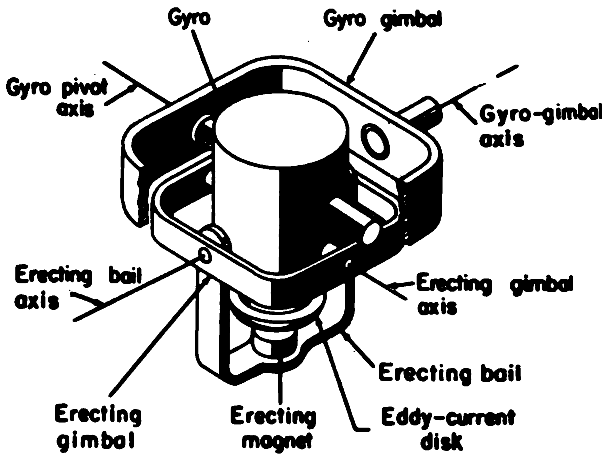
To overcome this difficulty, the point of applying torque must be moved. The torque point is moved by causing the outer gimbal to slowly and continuously rotate in the proper direction. With a small mercury tube, it will take some length of time for the mercury to flow from one tank to the other. By proper selection of gimbal rotation speed, the tanks may be displaced 90 degrees during the flow of the mercury. The torque will now be applied at a point which causes the gyro to precess in the proper direction so as to maintain the gyro spin axis vertical.

Another type of erection system is known as a magnetic erection system. In this system (fig. 5-15) a magnet, bail, and gimbal are suspended from the gyro on an axis below the gyro pivot axis. The magnet is free to swing about both the erection bail and gimbal axes and therefore acts like a pendulum which tends to remain perpendicular to the earth's surface. The eddy-current disk is mounted on the gyro shaft and spins with the gyro rotor. You will remember that when a conductor is moved in a magnetic field, current is induced in the conductor. The current in the disk produces a magnetic field which opposes the movement. The torque created causes the gyro to precess back to its center position.



12.145

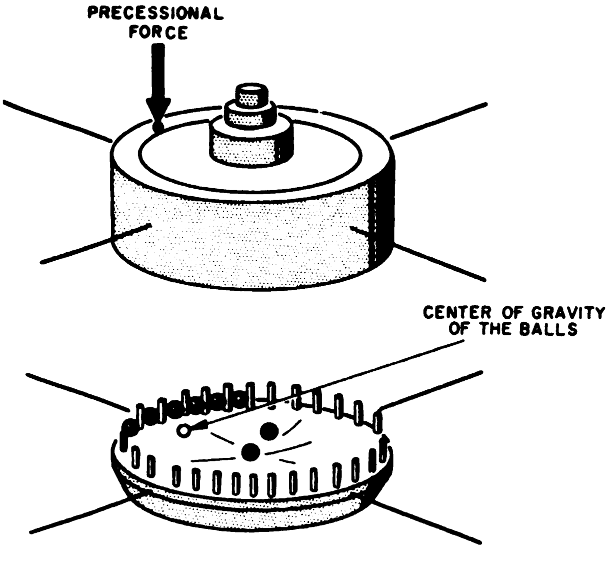
Figure 5-14.—Mercury erecting system.



166.37

Figure 5-15.—Magnetic erecting system.

A ball erector mechanism (fig. 5-16) is also used for maintaining the gyro spin axis vertical. This mechanism consists of a flat cylindrical enclosure suspended from the gyro case by means of a ring which also serves as a bearing surface. It is geared to the rotor shaft and rotates slowly about an axis parallel to the gyro spin axis. When the gyro is vertical, eight small balls are massed in the center of the concave surface of a disk in the bottom cover. Eighteen holder pins are equally spaced near the edge of the concave disk. When the gyro tilts, the balls roll to the lower side of the disk, where they are held loosely by the holder pins and carried ahead, in the direction of rotation, toward the higher side. As each ball reaches a point where it can drop past the holder pin, it falls across the disk and resumes its cycle. The center of gravity of the balls, so displaced, is at a point 90 degrees from the low point, in the direction of rotation. Thus, a torque is created which precesses the gyro back to a vertical position, causing the balls to cluster in the center of the disk, exerting no precessional force. The ball holder rotates in the same direction as the gyro, and is easily observed because of its slow speed.



27.186

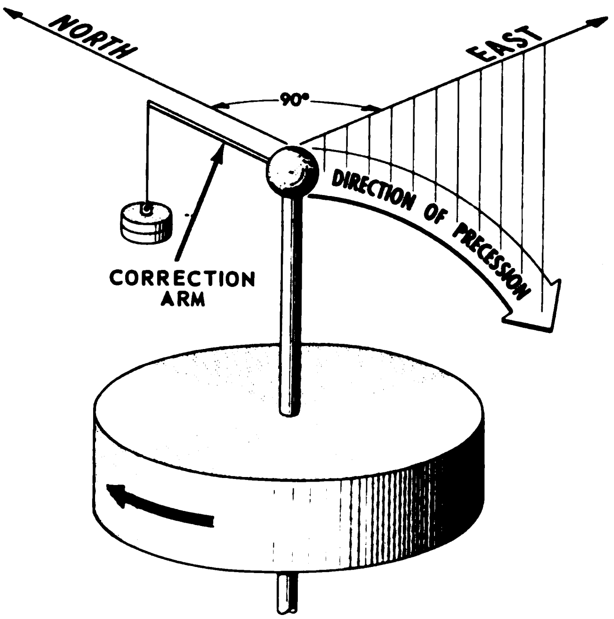
Figure 5-16.—Ball erector system.

An E-transformer pickoff, pendulum arrangeent may also be used in an erection system. or this application the moving element of the ansformer is a pendulum. Any displacement of e moving element causes an electrical output. his output may then be applied to some type of rquer to precess the gyro.

Many other types of erection systems may e found; but all will have basically the same nction which is to maintain the spin axis ertical.

Like the horizontal gyro, the vertical gyro s also subjected to vertical earth rate effect s well as horizontal earth rate effect. This ffect varies with the sine of latitude in which e gyro is operating and is maximum at the quator and zero or minimum at the poles. For the horizontal gyro, this effect is maximum t the poles and minimum at the equator.)

A common method for compensating for the ertical earth rate effect in the vertical gyro s by the use of a latitude correction weight as hown in figure 5-17. The weight is kept oriented orth and provides the proper force to cause he gyro to precess to the East at the same rate s the apparent Westward rotation. The rate of recession is controlled by moving the weight n or out along the correction arm which is marked n degrees of latitude.



12.149

Figure 5-17.—Latitude correction weight.

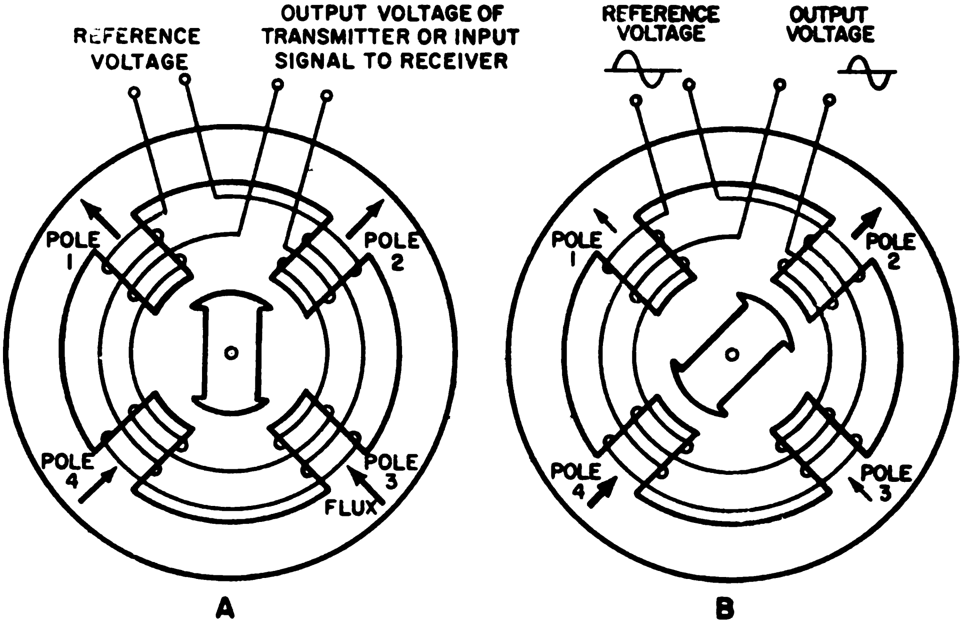
PICKOFFS AND TORQUERS

Gyros are used in some applications to position a device such as a gunsight mirror directly through gearing or other mechanical means. Gyros of this type are sometimes referred to as "brute force" gyros. Most gyro applications, however, require that gyro movement or movement of some other device in relation to the gyro be measured. This requires the use of some type of pickoff which converts mechanical movement into a corresponding electrical signal.

The E-transformers discussed in chapter 4 are the most common devices used as gyro pickoffs. Potentiometers, synchros, resolvers, and photoelectric cells are also used in some applications. Another fairly common electromechanical device used as a gyro pickoff is the microsyn transmitter described below.

MICROSYN TRANSMITTER

In the microsyn transmitter unit the four primary coils are connected in series and are excited by a 400-Hz reference voltage. Other frequencies are used, but 400-Hz is most common. The coils are wound so that the flux in pole 1 aids the flux in pole 4, and the flux in pole 2 aids the flux in pole 3. When the rotor is



55.26
Figure 5-18.—Microsyn transmitter; (A) Rotor at zero; (B) Rotor displaced to right.

in the zero position as shown in figure 5-18A, equal amounts of rotor iron are under each of the four pole faces. In this position, the pole 1-pole 4 flux through the rotor equals the pole 2-pole 3 flux through the rotor. Equal voltages are now induced in the secondary coils. These four secondary coils are also connected in series. The voltage induced in the pole 1 secondary aids the voltage induced in the pole 3 secondary. The combined voltages in the pole 1 and pole 3 secondaries oppose the combined voltages of the pole 2 and pole 4 secondaries. When the rotor is at the zero position, these two pairs of combined voltages are equal, and the output of the microsyn transmitter is zero.

When the rotor of the microsyn transmitter is turned to the right (fig. 5-18B) by a mechanical input, in this case gyro precession, the amount of rotor iron under poles 2 and 4 exceeds the amount of rotor iron under poles 1 and 3. The total voltage induces in the secondary coils of poles 2 and 4 now exceeds that induced in the secondary coils of pole 1 and pole 3. Under this condition the phase of the output voltage is that of the voltage induced in the secondary coils of poles 2 and 4, and the amplitude of the output voltage is equal to the voltage induced in secondary coils 2 and 4 minus the voltage induced in secondary coils 1 and 3. If the rotor of the microsyn is turned to the left, the magnitude of the output voltage equals the voltage induced in secondary coils 1 and 3 minus the voltage induced in secondary coils 2 and 4. Thus, the microsyn transmitter has an output voltage whose phase is determined by the direction of the rotor displacement from zero and whose amplitude is determined by the amount of this displacement.

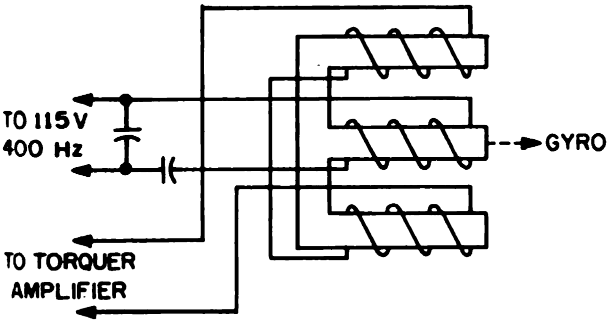
TORQUERS

In addition to the use of weights and other mechanical means, various types of electrical torquers are used to torque a gyro. Electrical torquers must be capable of producing torque in two directions about a null, the direction depending upon the phase or polarity of the error signal or pickoff signal. The torque is usually applied electromagnetically to the member to be torqued rather than by a mechanical connection. A mechanical connection causes friction which results in mechanical drift of the gyro.

A common type of torquer consists of an open-E rack structure of soft iron laminations, upon which are wound a control field (on the 2 outer legs) and a fixed or reference field (on he center leg) displaced 90 degrees to form an rrangement similar to a 2-phase induction motor fig. 5-19). The control fields are excited from he torquer amplifier output and the fixed or eference fields are excited from a 115-volt 00-Hz supply. When the torquer windings are nergized, a moving field is set up in the air ap. This field induces currents in the member o be torqued and a torque is developed that tends o drag the member along with the moving field. he magnitude of the torque is proportional to he strength of the signal fed to the control wind- ngs, and the direction of the torque depends pon the phasing of the control field voltage, hich may lead or lag the fixed field voltage by 0 electrical degrees. To obtain the correct phase elationship between the control and fixed fields, apacitors are used to shift the phase of the ixed field.

A 2-phase induction motor similar to the 2- hase a.c. servomotor is also used as a torquer n some applications. The motor stator is mounted n the gimbal and the rotor on the gimbal axis. he a.c. applied to the stator sets up a rotating nagnetic field which induces current in the rotor. he magnetic field caused by the rotor current nteracts with the rotating stator field and causes he rotor to follow. As the rotor moves it applies orque to the gyro.

The microsyn receiver is another device com- nonly used as a torquer. This unit is physically nd electrically identical to the transmitter (discussed earlier). The rotor, however, is free o turn and can be attached to the input shaft of gyro. When the reference voltage alone is pplied to the primary, the fields produced in he four primary coils will position the rotor to ero so that equal amounts of rotor iron are nder each of the poles. If a voltage in phase with the reference voltage is applied to the secondary coils, the flux produced in poles 2 and 4 (fig. 5-18) by these coils aids the flux produced by the primary coils. Meanwhile, the flux produced in poles 1 and 3 by the secondary coils opposes the flux produced by the primary coils. The magnetic field produced in poles 2 and 4 is stronger than that produced in poles 1 and 3. Therefore, a torque, exerted on the rotor, will attempt to increase the amount of rotor iron under poles 2 and 4.



27.164(175)
Figure 5-19.—Gyro torquer.

If the phase of the voltage applied to the secondary coils is reversed, the direction of the resultant torque will be reversed. Thus, the microsyn receiver produces a torque whose direction is determined by the phase relationship of the reference and signal voltages, and whose magnitude is determined by the amplitude of the signal voltage.

DIRECTIONAL, STABILIZING, AND RATE GYROS

As mentioned previously, gyros may be classified according to their degrees of freedom, that is, a single-degree of freedom (restrained) or two-degrees of freedom (free) gyro. Gyros are also sometimes classified as to the orientation of the spin axis (horizontal or vertical) and according to their application such as directional gyros, stabilizing gyros, and rate gyros.

DIRECTIONAL GYROS

The directional gyro is a free horizontal gyro that holds its position in azimuth and is used to show any deviation from a desired heading. It is not compensated for the effects of the earth's rotation and thus must be periodically leveled and set to the desired heading. The directional gyro is used extensively in Naval aircraft in conjunction with a magnetic compass for navigation purposes. It is also used to maintain alinement when making an instrument landing and as an aid in locating navigation stations.

Directional gyros are also used on surface ships and submarines when operating near the poles where special navigation techniques are required.

STABILIZING GYROS

Stabilizing gyros are used to establish a fixed reference from which movement or displacement can be measured. They may be used to establish horizontal and vertical references and may be used in groups of two or more to establish geometric planes of reference.

In addition to the basic components of a free gyro, stabilizing gyros have pickoffs for detecting and transmitting any movement from the stabilized reference. The pickoff outputs are used as error detector inputs to servosystems which function to stabilize the equipment concerned.

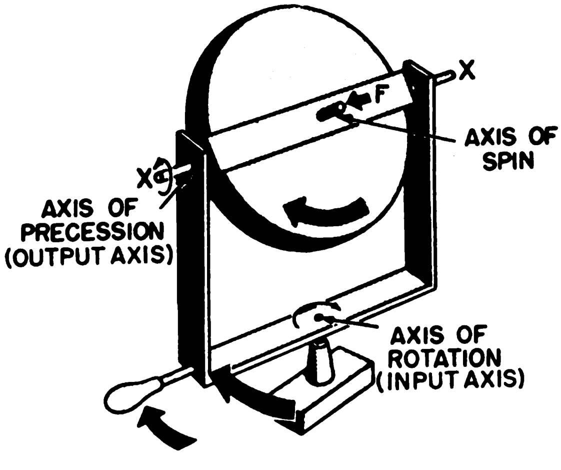
Stabilizing gyros are used to generate roll, pitch, and yaw (heading) signals in Navy ships and aircraft for use in systems such as automatic flight control systems and inertial navigation systems. They are also used in stabilizing radar antennas and launching platforms, and in many other shipboard and aircraft applications.

RATE GYROS

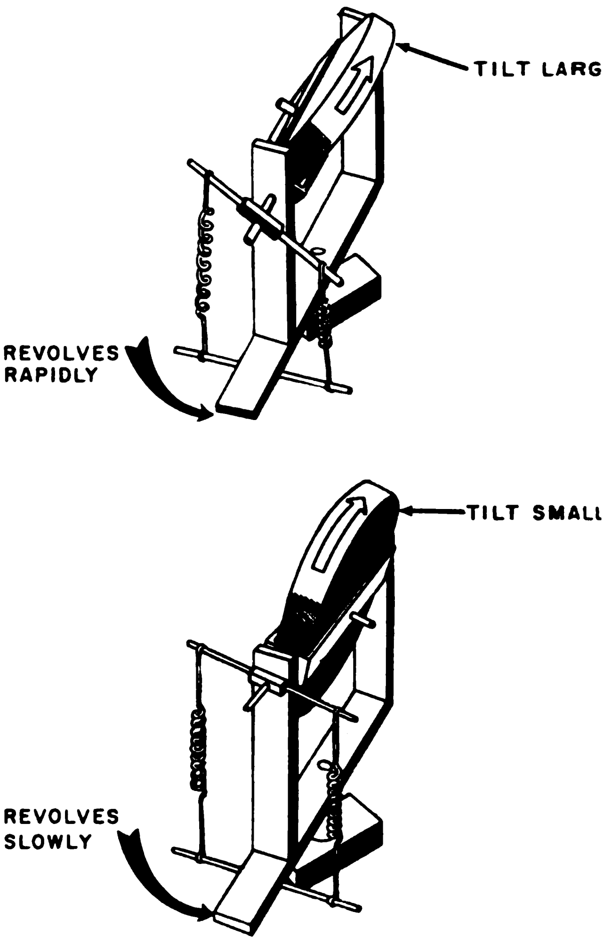
A rate gyro, (also called a rate-of-turn gyro) is a restrained gyro used to measure a rate of change. It accomplishes this by utilizing the property of precession as described in the following paragraphs.

You know that a force applied at F (fig. 5-20) will cause the gyro to precess at right angles to the force. Likewise, attempting to turn the gyro case will cause the same result. They gyro will precess as shown by the arrows, around the x-x axis.

Since the rate of precession is proportional to the applied force, you can increase the rate of precession by increasing the speed with which you are moving the gyro case (fig. 5-21). In other words, you have a RATE-OF-TURN GYRO. The FASTER you turn the gyro case, the MORE the GYRO will PRECESS, for the amount of precession is proportional to the rate of turn.


X
F
AXIS OF SPIN
X
AXIS OF PRECESSION (OUTPUT AXIS)
AXIS OF ROTATION (INPUT AXIS)

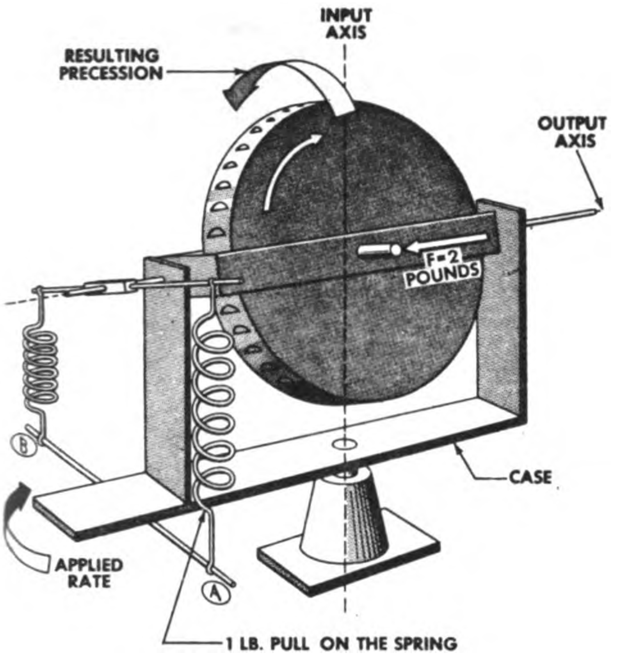
12.152.2
Figure 5-20.—Gyro precession.



12.152.3
Figure 5-21.—Precession is proportional to the rate-of-turn.

Figure 5-22 illustrates a method of restraining (controlling) the precession of a gyro to permit the calculation of a target rate. A pair of SPRINGS has been attached to the crossarm on the x-x shaft. These springs serve to restrain the FREE precession of the gyro. The gyro is harnessed to produce some useful work.

As a gyro precesses, it exerts a force which is proportional to the momentum of the spinning wheel and the applied force.



12.153
Figure 5-22.—Spring restrained rate gyro.

For example, suppose you rotate the gyro case at a speed which is proportional to applying a horizontal force of 2 pounds at F. Obviously, the gyro will precess; and as it does, it will cause the crossarm to pull up on spring A with a CERTAIN FORCE—say 1 pound. (This would vary with the length of the crossarm.)

If you CONTINUE to turn the gyro case at this rate, the precession of the gyro will continually exert a pull on the spring. More precisely, the gyro will precess until the 1-pound pull of the crossarm is exactly counterbalanced by the tension of the spring.

The gyro will continually try to precess farther, but since its pull is balanced by the tension of the spring, it will remain in a fixed position as shown in figure 5-22. That is, it will REMAIN in the PRECESSED POSITION as long as you CONTINUE TO ROTATE THE CASE AT THE SAME CONSTANT SPEED.

When you stop moving the gyro case, it is equivalent to removing the force at F, and the gyro stops precessing. The spring is still exerting a pull, however, so it pulls the crossarm back to the horizontal.

Suppose you rotated the case twice as fast as before. That would be equal to a 4-pound force at F and a resulting 2-pound pull by the crossarm on spring A. So the gyro would precess twice as far, before the tension on the restraining spring equaled the pull of the crossarm.

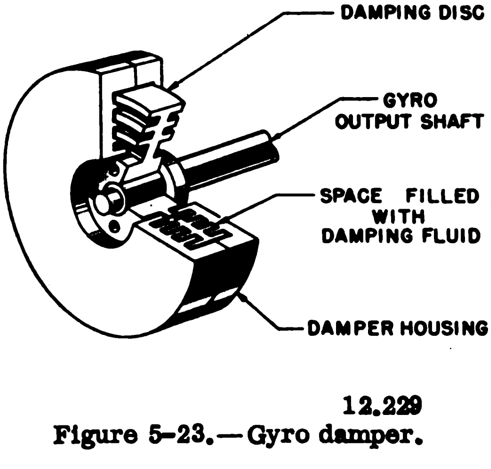
Thus the faster you rotate the gyro case the further the gyro will precess before the forces of the crossarm and spring are equal, and the gyro comes to rest.

To obtain a smooth output from a rate gyro, various types of damping systems are used. For example, a damping disk containing a viscous fluid which resists the rotation of the disk (fig. 5-23) may be attached to the gyro output shaft, or the gyro may be made to precess against the action of a dashpot. In other applications eddy-current disks are used to produce the damping effect. Other methods are also used. Any device that functions to slow the gyro response so that the gyro is not oversensitive to spurious peak movements is considered a damper.

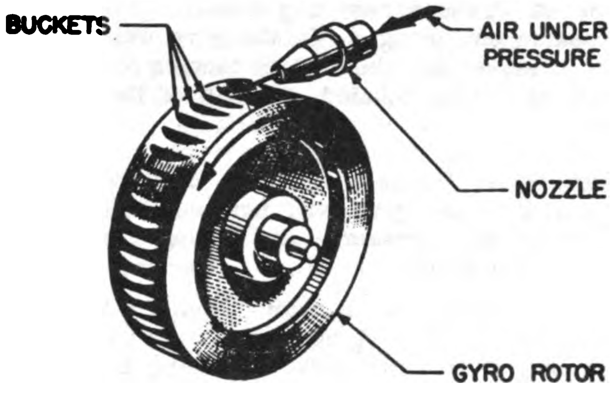
The length of time that a rate gyro requires to respond to an external turning force is called its SOLUTION TIME. This solution time is a function of the gyro design and the degree of damping.

In other applications, the springs of the rate gyro (fig. 5-22) may be replaced by torquers or other types of restraining devices and the output axis connected to some type of measuring device.

Rate gyros are used extensively in shipboard weapons systems and in aircraft. They are used, for example, to measure the angular rate of change of a target's position, and to measure the rate of change in the aircraft's roll, pitch, and yaw.



12.229
Figure 5-23.—Gyro damper.



175.39
Figure 5-24.—Air-driven gyro rotor.

GYRO CONSTRUCTION

Most gyro rotors are electrically driven. In some applications, however, a jet of air or gas may be used to drive the rotor. In special applications where the rotor must reach full speed in a short time, and the gyro is needed for only a short time, a spring or explosive charge may be used as the driving force.

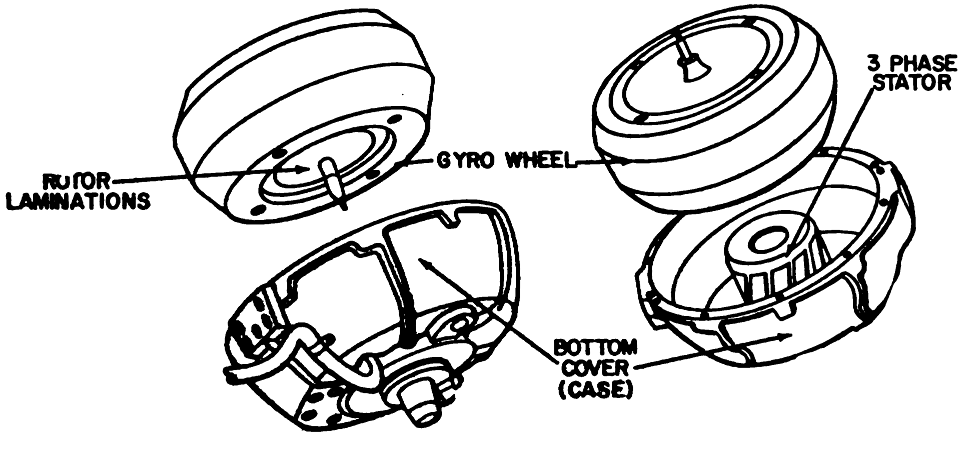
When air or some type of gas is used to drive the rotor, the rotor is constructed with turbine buckets as shown in figure 5-24.

When an electric motor is used as the driving force for a gyro, the motor is constructed differently than the conventional electric motor. For gyro applications, the rotor is usually designed to rotate around the outside of the stator as shown in figure 5-25. By making the rotor the outside of the motor, the greatest inertia and thus the greatest rigidity may be obtained for a given rotor weight.

Due to the high speeds involved (8000 to 24,000 r.p.m. or higher), most gyro units are hermetically sealed and rotate on special type, near frictionless, ball bearings. Gyros of the type shown in figure 5-25 turn in a vacuum. Other types of gyros are sealed in a sphere or cylinder and turn in some type of gas, usually helium.

ACCELEROMETERS

An accelerometer may be defined as a device which gives an indication, usually in the form of a voltage, proportional to the acceleration (changes in speed or direction) to which it is subjected. The operation of an accelerometer is based on the property of inertia. A simple demonstration of inertia happens to us almost every day. You know that if your automobile is subjected to acceleration in a forward direction, you are forced back in the seat. If your auto comes to a sudden stop, you are thrown forward. When your auto goes into a turn, you tend to be forced away from the direction of the turn—that is, if your auto turns left, you are forced to the right, and vice versa. This is in accordance with Newton's first law of motion as discussed earlier in this chapter.



175.40
Figure 5-25.—Electric motor-driven gyro.

If we replace the human in an auto with a mass suspended in an elastic mounting system (fig. 5-26), any acceleration of the auto will cause movement of the mass relative to the auto. The amount of displacement is proportional to the force causing the acceleration. The direction in which the mass moves in relation to the auto is opposite to the direction of the acceleration.

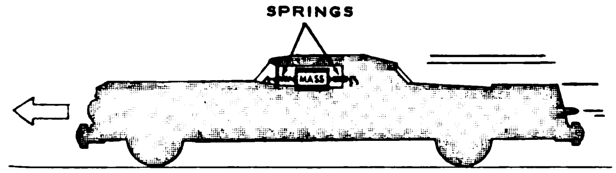
The movement of the mass is in accordance with Newton's second law of motion which states that when a body is acted on by a force, its resulting acceleration is proportional to the force and inversely proportional to the mass of the body.

When no acceleration is present, the mass in the figure will be at rest. When acceleration is present, the mass will lag in proportion to the acceleration force. In other words, the car moves but the mass wants to remain at rest.

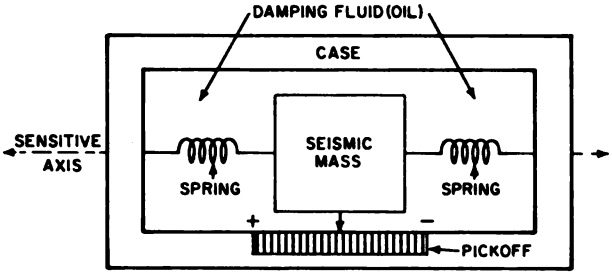
Accelerometers are used principally in inertial navigation and other aircraft systems, and in shipboard navigation and missile systems. The common types of accelerometers are described briefly in the following paragraphs.

LINEAR ACCELEROMETER

Figure 5-27 is a simplified drawing of a linear accelerometer. It consists of a mass, called the inertial mass, seismic mass, or proof mass, which is free to slide along the sensitive axis within the case. The movement of the mass is limited by the springs. When the case is accelerated, the seismic mass, because of its inertia, tends to remain stationary. This results in a relative movement of the mass with respect to the case. When the stretch of the springs overcomes the inertia of the mass, the springs cause the mass to stop moving with respect to the case. The displacement of the mass with respect to the case is directly proportional to the acceleration of the case. When the case stops accelerating, the springs return the mass to its zero position (the reference position). To keep the springs from causing the mass to overshoot and oscillate about the reference position, some form of damping is needed. This is usually supplied by using an oil-filled case with vanes for oil to bypass the mass.



33.130
Figure 5-26.—Auto with spring-suspended mass.



55.43
Figure 5-27.—Simplified linear accelerometer.

Accelerometers are sensitive to gravity when their sensing axis is positioned so that gravity can move or attempt to move the seismic mass. This is useful in that we can use gravity as a reference for calibration, but it can be a serious problem because of the errors it may cause in acceleration measurements. If the unit is placed with the sensing axis vertical, the mass will be displaced such that the output is one G, or one gravity. This is done for calibration; then when the sensitive axis is turned so that it is horizontal to the earth, the springs center the mass, and the output of the unit is zero.

ANGULAR ACCELEROMETER

The basic angular accelerometer shown in figure 5-28 works on the same principle as the linear accelerometer previously described. The two types differ in one respect—the angular accelerometer can be considered as a small servo or closed-loop system, whereas the linear accelerometer is of an open-loop nature.

The angular accelerometer consists of a mass, pickoff, damping fluid, torquer, and an amplifier. All of these elements are usually packaged as a unit.

Briefly, this is how the device works. When the vehicle in which the accelerometer is placed, experiences an angular acceleration about the accelerometer's sensitive axis, the mass develops a displacement. The position of the mass is measured by the pickoff. The pickoff can be a precision pot, E-transformer, or any sensitive position-measuring device. In any case, the output voltage from the pickoff is proportional

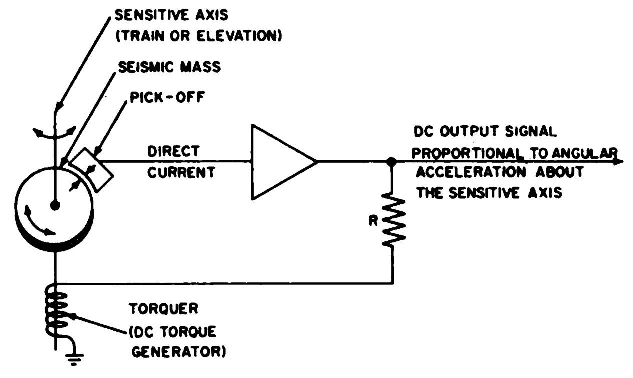


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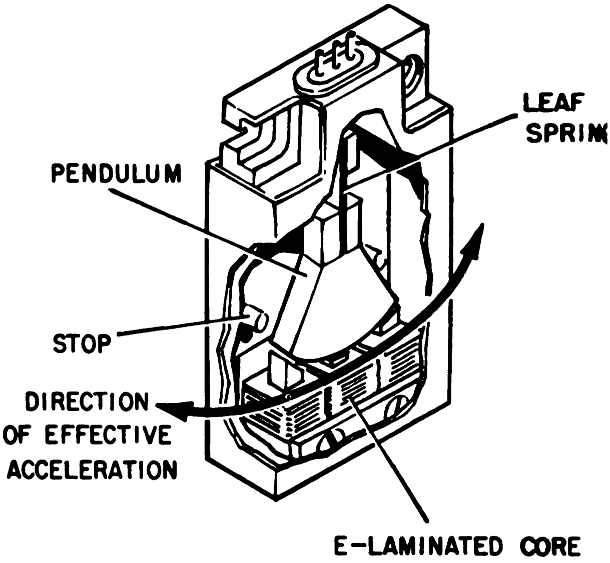
Figure 5-28.—Simplified angular accelerometer.



175.41
Figure 5-29.—E-transformer accelerometer.

to angular acceleration. This voltage is amplified by a high gain amplifier whose output is a current proportional to acceleration. This current is applied to the torquer to force the mass back to its original position and thus cancel the signal. This movement is proportional to the angular acceleration experienced by the system. This device employs angular motion of a mass as an indication of acceleration. It can also be used to measure linear acceleration along the input axis.

E-TRANSFORMER ACCELEROMETER

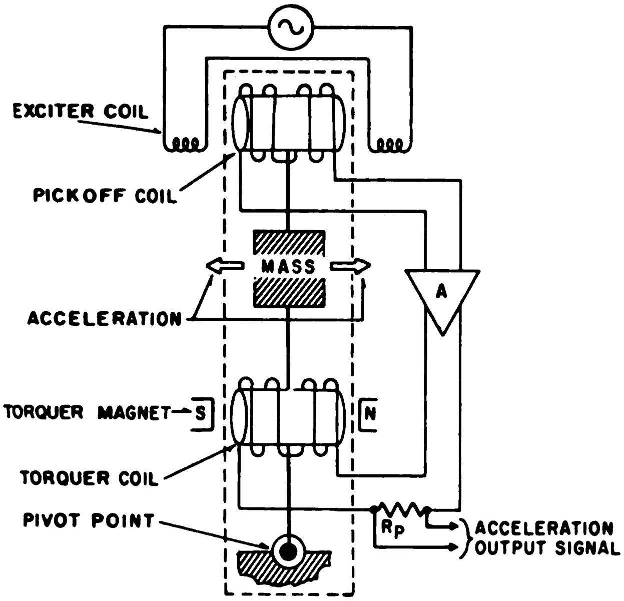
The E-transformer accelerometer (fig. 5-29) consists of a mass suspended from a calibrated leaf spring in a manner similar to a pendulum. The mass is effectively the armature of an E-transformer of the type used as an error detector in a servosystem. The mass of the accelerometer is enclosed within a case that is filled with a damping liquid which helps keep the pendulum from oscillating. The accelerometer is mounted so that acceleration in only the desired geometrical plane is detected.

Referring to figure 5-29 it should be noted that when there is no acceleration, the pendulum remains centered and the accelerometer output is zero. However, when there is acceleration the mass or pendulum swings in the directpon opposite to that of the acceleration, causing an output from the E-transformer. Since the amplitude of the pendulum swing is proportional to the amplitude of the acceleration to which it is subjected, the output of the device is indicative of both the direction and amplitude of the acceleration. This output is within the limits of the equipment and is limited by physical stops.

FORCE BALANCE ACCELEROMETER

An accelerometer commonly used with inertial navigation systems is the force balance accelerometer. A schematic representation of this type is shown in figure 5-30. The pickoff coil, the mass, and the torquer coils are all situated on a common movable shaft, which has the ability to make a partial rotation about its pivot point axis.

With zero acceleration, the induced current in the pickoff coil is balanced and the torquer coils keep the mass in the null position. However, as acceleration occurs, the mass velocity tends to remain constant. Since the stationary portion of the accelerometer assumes the new velocity, it causes one of the exciter coils to move closer to the pickoff coil and the other exciter coil to move farther away. Which exciter coil comes nearer to the pickoff coil depends upon the direction of acceleration. As the distance changes between the exciter coils and the pickoff coil, an unbalanced condition



175.42

Figure 5-30.—Force balance accelerometer.

occurs in the pickoff coil circuit. This causes an error signal to be induced, which is amplified, changed to d.c., and applied to the torquer coils. Windings of all the coils are such that any unbalanced condition in the circuits produces a bucking (or reverse) current which counteracts the field of the torquer magnets and keeps the mass near mechanical zero. As the acceleration force increases, the amount of current necessary to keep the mass near the null position also increases. Since the current is proportional to the acceleration, the voltage drop across Rp, a precision resistor, is also indicative of acceleration. This voltage drop, ERp, then becomes the electrical output from the accelerometer.

PULSE COUNTING ACCELEROMETER

Though the output of a force balance accelerometer is an analog current proportional to acceleration, there is need for accelerometer output signals to be in digital form. Pulse counting accelerometers satisfy this need, since their pulse output can be supplied directly to computers. A schematic of a pulse counting accelerometer circuit is shown in figure 5-31A. A cutaway view is shown in figure 5-31B.

With velocity remaining constant, the brush spring holds the mass at null and the brush rests on the reset contact of the switch. As acceleration occurs, the tendency of the mass to remain at a constant velocity causes the spring to compress. In doing so, it allows the brush to move off the reset contact; and if acceleration is great enough, the brush will pass over the switch contacts for acceleration levels 1, 2, 3, and 4. These levels are determined by the stiffness of the spring.

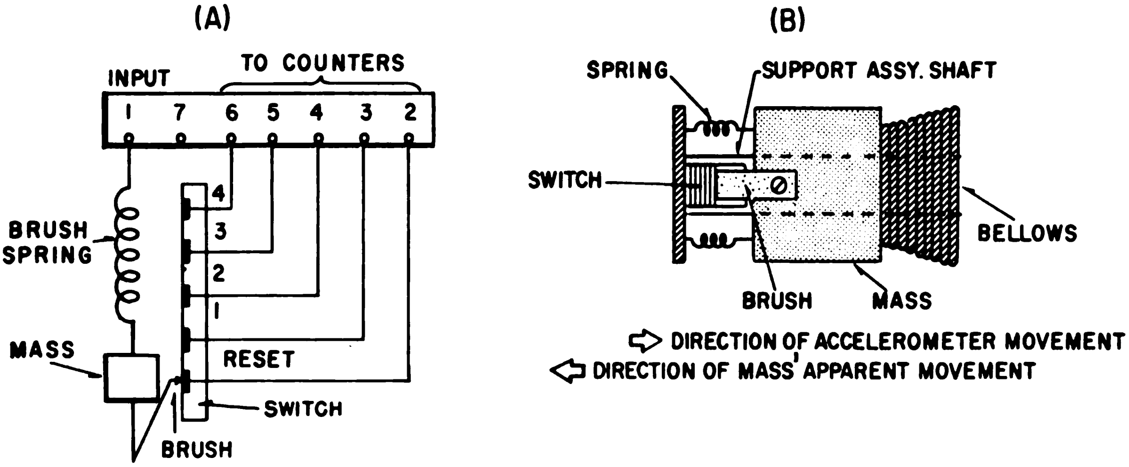


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Figure 5-31.—Pulse counting accelerometer.

As the brush passes over each contact (in a positive direction), an output pulse from each contact is coupled to one of four counters. This advances the counter one-half count. The accelerometer is so designed that as acceleration decreases and the mass tends to assume the new velocity, the counters will not advance the remaining half count until the brush once again touches the reset contact. With this type of pulse output, it is possible to record each time gravity forces have reached a predetermined level.

CHAPTER 6

SYSTEM APPLICATIONS

This chapter presents a basic description of some of the shipboard and aircraft systems that utilize many of the components (such as synchros, servos, resolvers, gyros, and accelerometers) discussed in this training manual. The purpose of the chapter is to show how these components function in the various systems rather than to describe specific shipboard or aircraft systems.

GUN FIRE CONTROL SYSTEM

The major components of a shipboard gun fire control system are shown in figure 6-1. The director provides the target position data and is the control unit of the system. The stable element (by the use of a vertical gyro) provides the corrections for the roll and pitch of the ship. The computer receives data from the director, stable element, and other sources, and functions to compute and transmit the gun orders required to keep the guns pointed at the predicted position of the target.

FLOW OF DATA

Synchro transmission systems are used to provide the flow of data between the major units of the system. The director (fig. 6-1) locates a target's position in terms of range, bearing (train), and elevation and transmits these values to the computer. (Once acquired, a target may be tracked either by telescopes or by radar.) As the target is tracked, train and elevation data are transmitted continuously to the computer. Range of the target may be measured and transmitted either by radar or by a unit known as a rangefinder.

The computer receives the basic range, bearing, and elevation data from the director and transmits train and elevation gun orders corrected for the speed and direction of the wind, and the roll, pitch, speed, and heading of the ship. The computer also computes and transmits other data such as sight angle and deflection, projectile fuse settings, and parallax. In addition, the computer generates and transmits to the director, rates of target motion (generated train, elevation, and range). These changes are used in conjunction with level and crosslevel data from the stable element to hold the director telescopes, rangefinder, and radar on the target automatically.

MODES OF OPERATION

In most systems, the director may be moved in train and elevation manually by geared handwheels (manual control mode), or by power drives which usually are closed loop amplidyne servosystems of the type discussed in chapter 4. In the local control mode, the power drives are controlled by synchro signals originating at the director. In the automatic control mode, the power drives are controlled by the generated signals from the computer.

Figure 6-2 is a simplified diagram of the director train servoloop connected for radar tracking in the automatic mode. Basically, both train and elevation servoloops consist of two servosystems which function together to keep the director on the target. One servosystem (containing the radar) detects director position error by measuring target displacement from the line of sight (LOS). The other system (containing the computer) detects position error by comparing observed target position with the computer's generated target position. The outputs of the two servosystems are combined in the CDX (fig. 6-2). The CDX output is fed to the stator of a CT. The CT output provides the error signal input to the amplidyne servosystem which moves the director.

The gun mounts are also trained and elevated by power drives either in local or automatic control similar to the director. In local control, the power drives are controlled by signals

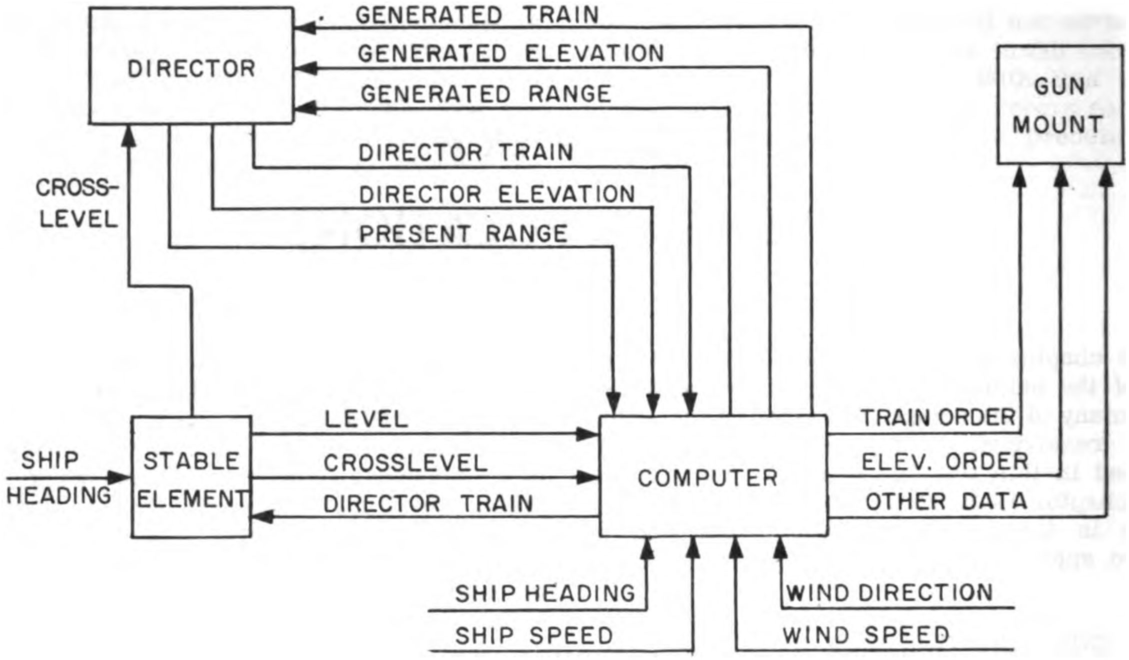

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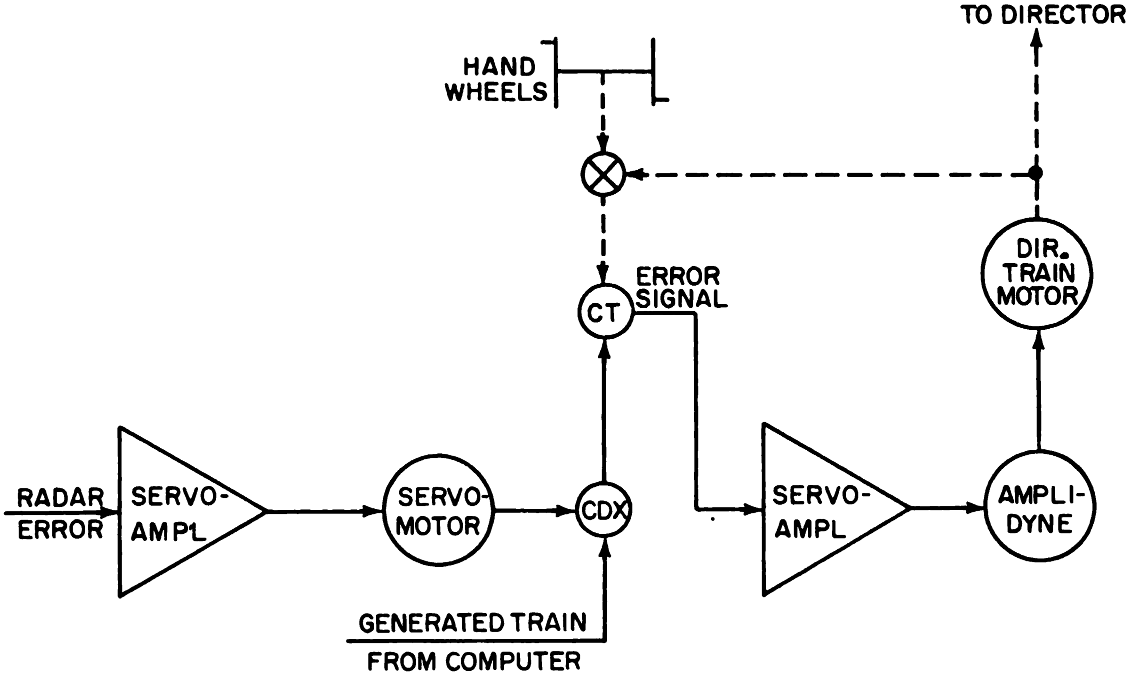
Figure 6-1.—Gun fire control system.



175.45
Figure 6-2.—Director train servoloop.

originating at the mount. In automatic control, they are controlled by the gun order signals from the computer. In some systems the gun mounts may be trained and elevated manually.

The gun mount power drives may be amplidyne servosystems, electrohydraulic servosystems, or servosystems using SCR power amplifiers as discussed in chapter 4.

GYROCOMPASS SYSTEMS

A gyrocompass may be defined as a directional gyro with the extra associated equipment to make it seek and continuously point North. A gyrocompass system includes the gyrocompass and all other associated equipment and subsystems necessary to supply heading data to all of the required locations in the ship or aircraft.

SHIPBOARD SYSTEMS

Basically, a shipboard gyrocompass system includes one or more gyrocompasses, a means for generating and transmitting ship's heading data, and provisions for indicating this data at the required locations throughout the ship.

As stated in chapter 5, the undamped gyrocompass instead of continuously pointing North, oscillates back and forth across the meridian. The time required for one complete cycle of this oscillation is called a PERIOD OF OSCILLATION and is expressed in minutes. For a given wheel at a particular spot on the earth's surface, this period is the same regardless of the angle through which the wheel oscillates. The period of oscillation of a North-seeking gyrocompass is determined by the size, shape, and speed of the rotor, the type of system used to make the gyro North-seeking, and the latitude in which the gyro is operating.

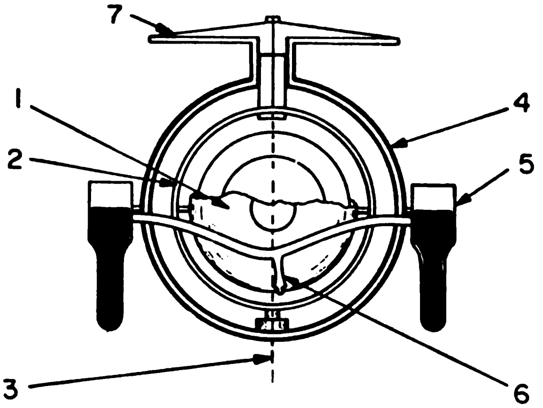
Damping the Oscillations

The north-seeking gyroscope can never settle in the desired position as long as it oscillates across the meridian. Therefore, some means must be provided to suppress, or damp, the oscillations by reducing the size of successive swings past the meridian until the swinging is stopped. When damped, the north-seeking gyroscope (1) settles with the tilt that is necessary to cancel the effect of the earth's rotation and (2) gives a continuous indication of true north. The time required for effective damping is about 4 hours for most shipboard gyrocompasses. Some shipboard gyrocompasses are provided with fast settling systems which greatly reduce the time required for damping during starting.

Oscillations are damped in gyrocompasses utilizing the mercury ballistic by employing a portion of the torque produced by the action of gravity upon the mercury ballistic to remove some of the tilt given the rotor axle by the rotation of the earth.

In the mercury ballistic described in chapter 5 the tanks are attached directly to the bearings at the ends of the shaft. In the actual compass the ballistic is pivoted on studs and bearings on an outside ring, called the phantom ring, in such a way that its only point of contact with the gyroscopic element is through a connecting arm, or link, which bears against the bottom of the case in which the rotor spins (fig. 6-3). The rotor case corresponds to the inner ring of a gyroscope and holds the bearings on which the axle turns.

If the point of connection between the mercury ballistic and the rotor case is in the line of the vertical axis the only torque that can be exerted by the mercury ballistic is about the horizontal axis, and the resulting precession is only about the vertical axis. Thus, the compass would



1. ROTOR CASE
2. VERTICAL RING
3. CENTER LINE
4. PHANTOM ELEMENT
5. MERCURY BALLISTIC
6. OFFSET ARM CONNECTION
7. COMPASS CARD

77.206

Figure 6-3.—Elements of a basic shipboard gyrocompass.

oscillate only back and forth across the meridian. However, if this point of connection between the ballistic and the rotor case is set a fraction of an inch to the east of the vertical axis (fig. 6-3), the force exerted by the mercury ballistic is applied about both the horizontal and the vertical axes. Precession then results about both the vertical and the horizontal axes. Precession about the horizontal axis is much slower than precession about the vertical axis because the point of connection is offset from the vertical axis only a small amount.

With the compass displaced 30° E of the meridian and level (point A, fig. 6-4), the earth's rotation will cause the north axle to rise. When the north end rises it causes a transfer of mercury to the south tank. Gravity action on this excess of mercury in the south tank causes torques to be exerted about both the horizontal and vertical axes. The torque about the horizontal axis causes precession of the north end of the gyrocompass axle to the west about the vertical axis. The torque about the vertical axis causes precession of the north end of the gyrocompass axle downward about the horizontal axis. At this time the precession about the horizontal axis opposes apparent rotation about the horizontal axis. The precession about the vertical axis will cause the compass to precess to the meridian. However, the compass cannot remain on the meridian (point B, fig. 6-4), because at this time it has its maximum tilt and therefore maximum rate of precession about the vertical axis. As the gyro precesses past the meridian, the direction of apparent rotation about the horizontal axis and the direction of precession about the horizontal axis are now both downward. This action causes the gyro to become level (point C, fig. 6-4). When the axle becomes level, precession ceases as there are no torques being applied by the mercury ballistic. If the proper (correct) torques have been applied, the compass would be only 10° W of the meridian, reducing the oscillation by 66-2/3 percent. However, as the earth continues to rotate, the compass will not remain level. Apparent rotation about the horizontal axis causes the north axle to tilt downward. This action causes a transfer of mercury to the north tank. Gravity action on this excess of mercury in the north tank will produce torques about both the horizontal and vertical axes. The torque about the horizontal axis will cause precession about the vertical axis, the north end moving toward the east. The torque about the vertical axis will cause precession about the horizontal axis, the north end moving upward, again opposing apparent rotation about the horizontal axis. The precession about the vertical axis will cause the gyro to precess to the meridian (point D, fig. 6-4). However, it cannot remain in the meridian because at this time it has maximum tilt, therefore maximum, rate of precession, causing the gyro to precess past the meridian. Now that the north axle is again east of the meridian, the apparent rotation about the horizontal axis and the direction of precession about the horizontal axis both cause the north axle to become level (point E, fig. 6-4) more quickly. At this time the compass would be approximately 3-1/3° east of the meridian. This damping action would continue for approximately 2-1/2 oscillations, and the compass would then settle on the meridian.

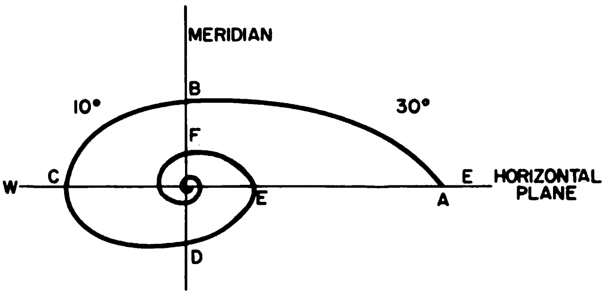


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Figure 6-4.— Path followed by the North axle of a damped gyrocompass.

Basic System

The major components of a shipboard gyrocompass system are the master gyrocompass, the gyrocompass switchboard, the power supply, and the speed and latitude corrector unit as shown in figure 6-5. The master gyrocompass includes the gyro unit, gimbals, supports, and other associated equipment necessary to give the gyro unit the two degrees of freedom and make it North seeking, and the equipment required for generating and transmitting ship's heading data. The complete unit is enclosed within a housing called a binnacle.

The gyro units used in shipboard gyrocompasses are special type 3-phase induction motors. Most of them either rotate in a vacuum in a sealed case similar to figure 5-25 in chapter 5, or in a sealed sphere called a gyrosphere as shown in figure 6-6. The sealed case gyro unit

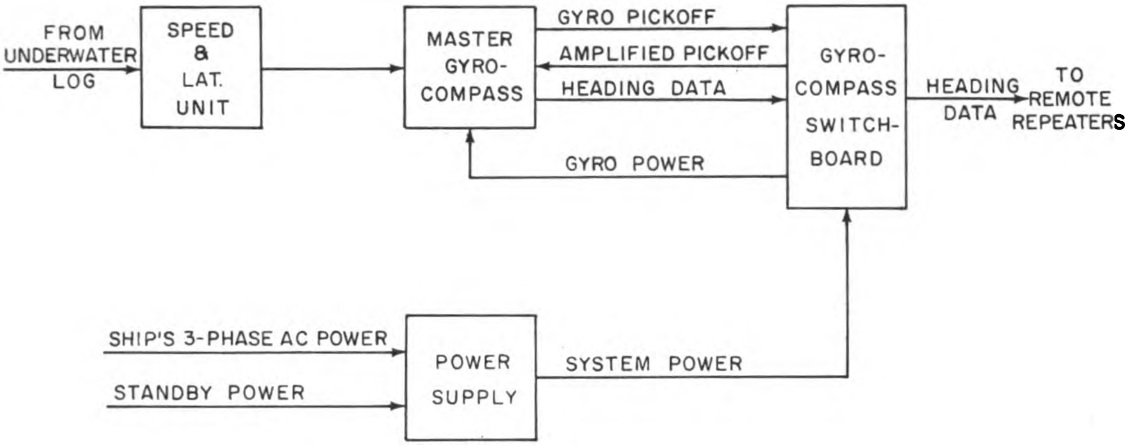

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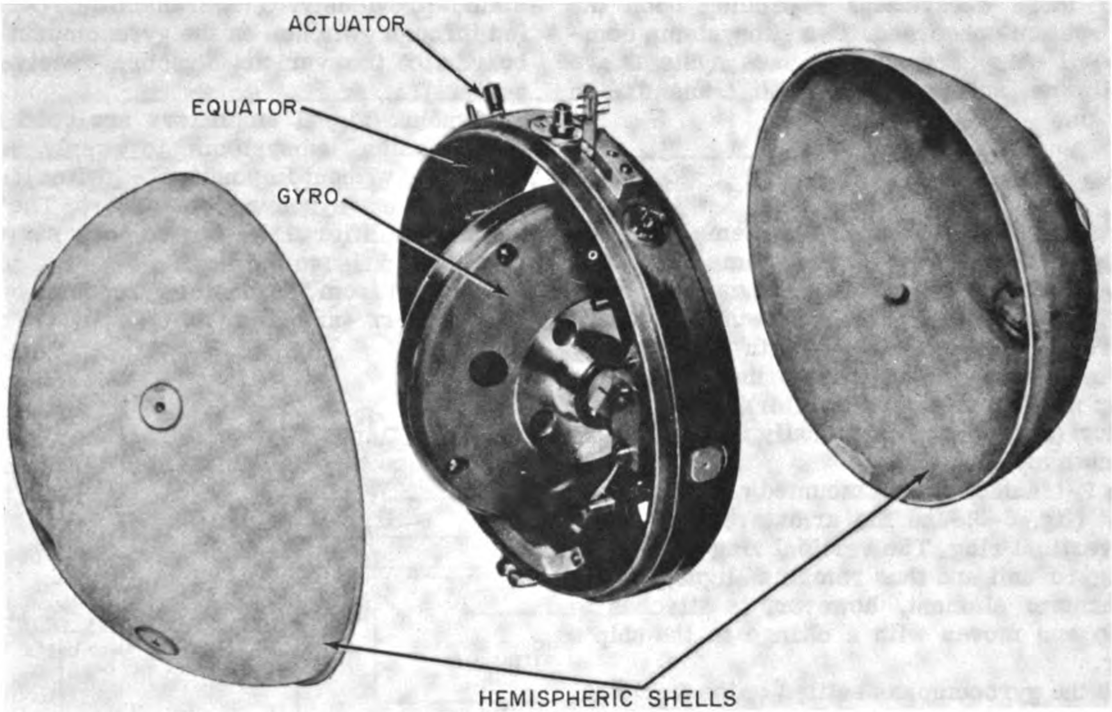
Figure 6-5.—Major components of a shipboard gyrocompass system.



7.173
Figure 6-6.—Exploded view of gyrosphere.

hangs on a wire suspension within the binnacle, whereas the sealed sphere type floats in oil.

The gyrocompass switchboard (fig. 6-5) mounts all of the meters, amplifiers, switches, and controls necessary for the operation and monitoring of the system.

The gyrocompass power supply provides the a.c. and d.c. electrical power for the operation of the system. Speed regulated motorgenerator (MG) sets are used in some installations with a standby battery supply. Other systems use the ship's 3-phase supply (regulated), and solid state rectifiers as the normal supply with batteries and a 3-phase static type inverter as the standby supply. Modern submarine gyrocompass power supplied use a 3-phase static inverter to convert the submarine's d.c. power to a closely regulated 3-phase a.c. for the normal supply. Batteries are used as the standby supply.

The speed and latitude corrector unit (fig. 6-5) operates in conjunction with a speed and latitude corrector mechanism on the master gyrocompass to compensate the gyro for the effects of the ship's speed and the rotation of the earth.

Shipboard gyrocompass systems may include two or more subsystems depending upon the type of system concerned. Two subsystems common to all shipboard gyrocompass systems are the followup subsystem and the transmission subsystem.

Followup Subsystem

Gyrocompass followup subsystems are essentially closed loop servosystems in which changes in the ship's heading are used as error signals. For example, the followup subsystem for gyrocompasses equipped with the mercury ballistic includes an E-transformer pickoff, a followup amplifier (servoamplifier), and a followup motor (servomotor), generally referred to as an azimuth motor.

The E-transformer is mounted on the phantom element (fig. 6-3) and the armature is mounted on the vertical ring. The vertical ring is attached to the gyro unit and thus remains aligned North. The phantom element, however, is attached to the ship and moves with a change in the ship's heading.

With the gyrocompass settled on the meridian, the phantom element is in alignment with the vertical ring, and the compass card indicates the ship's heading. In this neutral position, the voltages induced in the two secondary coils of the E-transformer are equal in magnitude but differ in phase by 180°; therefore there is no error signal input to the followup amplifier. When the E-transformer is moved to the right or left due to a change in the ship's heading, the E-transformer produces an output signal voltage whose magnitude depends upon the amount of the displacement and whose phase is determined by the direction of the displacement.

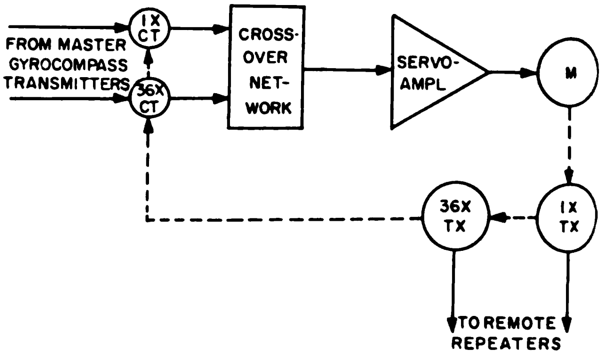
The pickoff signal from the E-transformer is amplified by the followup amplifier located on the gyrocompass switchboard (fig. 6-5) and fed to the azimuth motor on the master gyrocompass. The azimuth motor drives the phantom element into alignment with the vertical ring, and also drives the compass card and the rotors of synchro transmitters which transmit heading data to the gyrocompass switchboard.

Transmission Subsystem

Gyrocompass transmission subsystems are synchro systems which provide the means for transmitting and indicating ship's heading data. Dual-speed synchro systems are generally used. The synchro transmitters (usually 1 and 36 speed) are driven by the azimuth motor as stated previously. The transmitter outputs are fed through switches on the gyrocompass switchboard to the various synchro receivers (repeaters).

Synchro signal amplifiers are used in some transmission subsystems to supply additional repeaters without imposing the load on the master gyrocompass synchro transmitters. The synchro signal amplifier is a closed loop servosystem as shown in figure 6-7.

Outputs from the master gyrocompass synchro transmitters are fed to CTs in the synchro



175.47

Figure 6-7.—Synchro signal amplifier.

signal amplifier (fig. 6-7). The crossover network functions to select the proper input to the servoamplifier (as described in chapter 4). The synchro transmitters driven by the servomotor, M, are relatively large compared to the master gyrocompass transmitters and thus are capable of positioning a greater number of repeaters.

Other Subsystems

Figure 6-8 shows a simplified diagram of a shipboard gyrocompass system which includes leveling and azimuth control subsystems. The gyro unit in this system is enclosed in a gyrosphere (as shown in figure 6-6) and floated in oil.

The followup subsystem (fig. 6-8) includes the azimuth control amplifier, the azimuth control torquer, and the latitude resolver. This subsystem functions to produce a torque about the gyro horizontal axis causing the necessary precession about the vertical axis toward the meridian to make the gyro North-seeking.

The azimuth control torquer (which is similar to the gyro torquer shown in figure 5-19 in chapter 5) is the output element of the subsystem which applies the torque about the gyro horizontal axis. The torquer is supplied from the output of the azimuth control amplifier whose input is the amplified gyro tilt signal compensated for vertical earth rate. The gyro tilt signal is supplied by an electrolytic bubble level as discussed in chapter 5.

The latitude resolver (fig. 6-8) provides the proper signal voltage to the azimuth control amplifier to compensate the gyro for the effects of vertical earth rate. As mentioned in chapter 5, vertical earth rate effect is proportional to the product of earth rate and the sine of the latitude in which the gyro is operating. The rotor of the latitude resolver is excited with a reference voltage which represents earth rate and the rotor is positioned manually to the angle corresponding to the local latitude. The output of the resolver sine winding then, provides the vertical earth rate compensating signal.

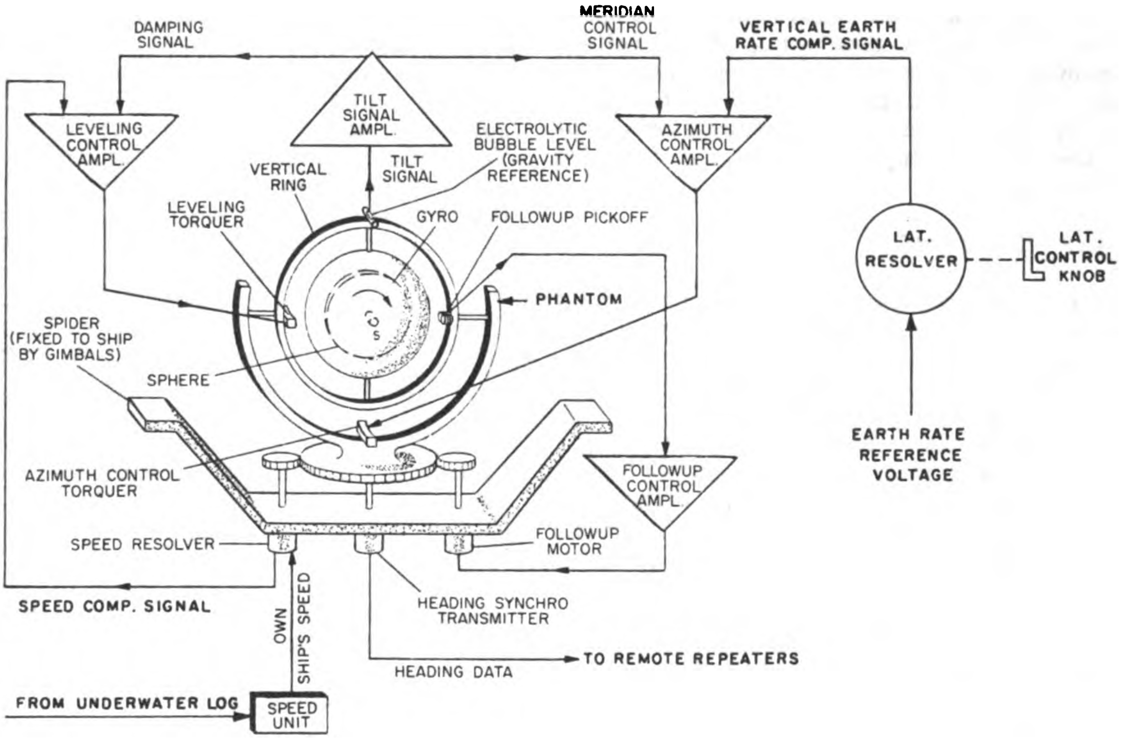


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Figure 6-8.—Simplified diagram of a shipboard gyrocompass system.

The leveling control subsystem consists of the leveling control amplifier, the leveling torquer, and the speed corrector unit. This subsystem function to apply a torque about the gyro vertical axis causing the gyro to assume a level position. The leveling torquer (which is identical to the azimuth control torquer) is supplied by the output of the leveling control amplifier whose input is the amplified gyro tilt signal compensated for ship's speed.

If a ship is traveling on a north-south course, as it follows the curvature of the earth, the north end of the gyro would appear to tilt. For a northerly course, the resultant tilt signal will cause the gyro to precess to the west, while a southerly course will cause precession in the opposite direction. If the ship's course is east-west, however, the ship's motion would have no tendency to tilt the gyro as the ship's direction of travel would be parallel to the plane of the gyro. The rate of gyro tilt depends upon the speed of the ship in a northerly or southerly direction, and is equal to the ship's speed times the cosine of the ship's course.

The speed corrector unit (fig. 6-8) receives the ship's speed input from the underwater log and develops a signal voltage output that is proportional to the ship's speed. This speed signal voltage is applied to the rotor of the speed resolver. The speed resolver (with a voltage representing ship's speed impressed on its rotor and the rotor positioned relative to the ship's course by the azimuth control subsystem) provides the speed compensating signal from its cosine winding.

AIRCRAFT SYSTEMS

Aircraft gyrocompass systems utilize many of the same types of components (such as synchros, servos, pickoffs, and torquers) as shipboard systems. The components in aircraft systems, including the gyro unit, are smaller and more compact than those used in shipboard systems, however their functions are the same.

As mentioned in chapter 5, the directional gyro is used in conjunction with a magnetic compass transmitter in many aircraft compass systems. In this combination, the directional gyro due to its slow precessional rate does not respond to the short-period oscillations of the magnetic compass, but rather to the average output. Thus the directional gyro provides a heading output that retains the long-period accuracy of the average magnetic compass reading.

The magnetic compass transmitter is als used in conjunction with a gyro unit that i essentially a gyrocompass. A simplified bloc diagram of a system of this type is shown i figure 6-9.

Magnetic Compass Transmitter

The magnetic compass transmitter (fig. 6-9 generates a signal similar to a synchro transmitter signal which corresponds to the magneti heading of the aircraft. The nomenclature an physical appearance of these transmitters var depending upon the type of compass system, however they all function on the same principles The unit is usually hemispherical in shape an only a few inches high so that it can be mounte within the wing or tail of the aircraft wher magnetic disturbances are minimum.

The sensing element of the transmitter (usuall called a flux valve) consists of an exciter coi and three pickoff coils wound on a laminate core mounted so that it is free to swing like pendulum within a sealed case. The element is mounted pendulously so that it will respond only to the horizontal component of the earth's magnetic field. A damping fluid in the sealed case prevents the element from excessive swinging during flight.

The laminated core of the sensing element is shaped like a three-spoked wheel with the rim split between the spokes as shown in figure 6-10. Three pickoff coils (one wound around each spoke) are connected in a wye configuration to form the fluxgate winding (6-10C). At the hub of the flux valve the spokes are all connected together by a core which could be compared to the axle. The exciter coil is wound around this axle.

The number of lines of flux set up by the earth's magnetic field will vary in the spider legs depending upon the heading of the aircraft (fig. 6-10A and B). By exciting the core with a.c., these lines of flux are caused to alternate back and forth across the pickoff coils. Thus the output of the fluxgate winding is a combination of voltages which correspond to the aircraft heading. This output may be fed to a heading indicator (similar to a synchro receiver) to indicate the heading of the aircraft, or may supply the stator of a CT as in figure 6-9.

Functional Description

The compass system (fig. 6-9) has two modes of operation; magnetic and gyro. In the magnetic

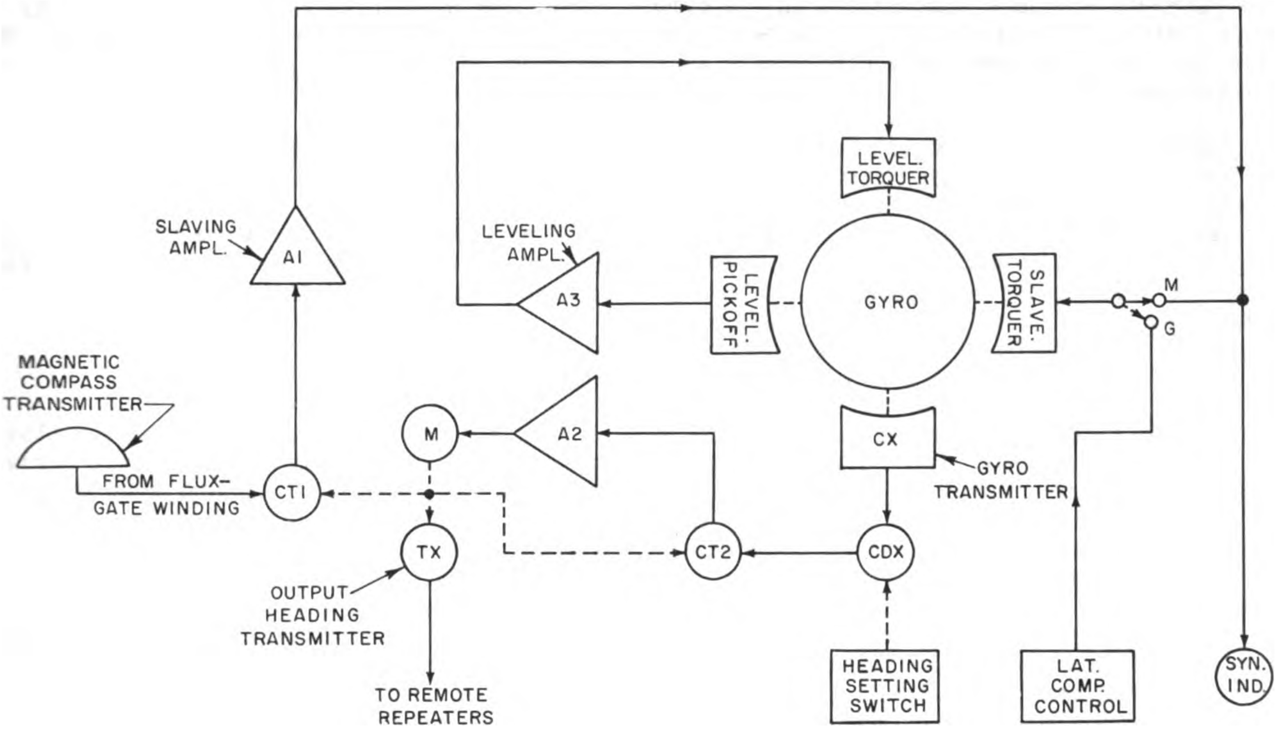

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Figure 6-9.—Simplified diagram of an aircraft gyrocompass system.

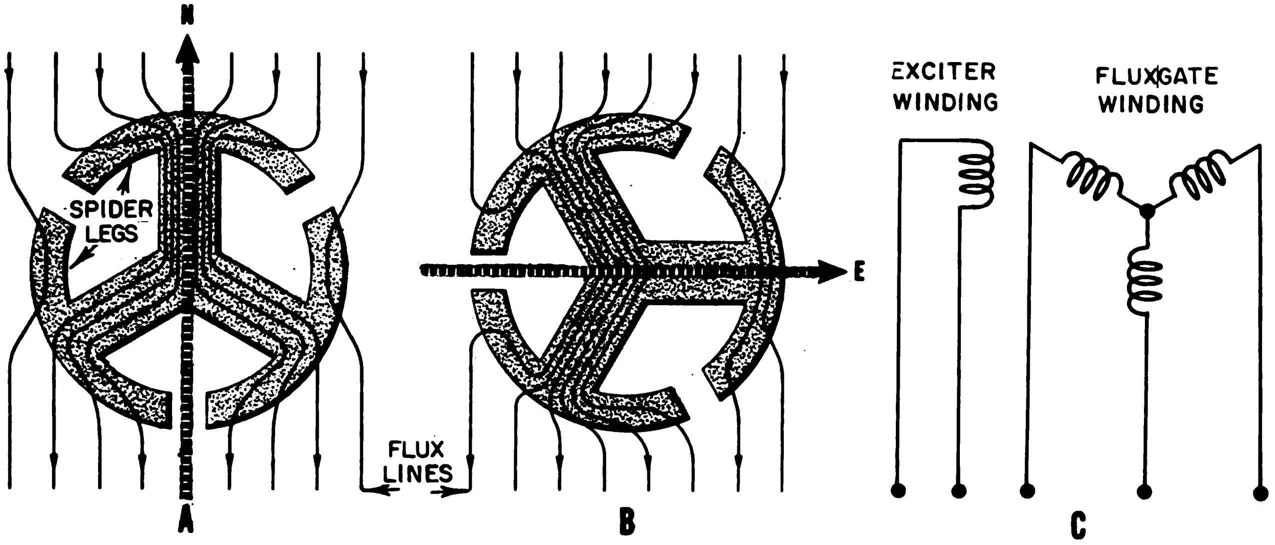

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Figure 6-10.—Flux valve; (A) Aircraft heading North; (B) Aircraft heading East; (C) Simplified schematic.

mode, the gyro is controlled by the output of the magnetic compass transmitter. In the gyro mode, latitude compensation is applied to the gyro and the gyro operates independently as a gyrocompass.

MAGNETIC MODE.—When power is applied to the system in the magnetic mode of operation (shown in fig. 6-9), synchro control transformer CT2 delivers an error signal to servoamplifier (A2). The servomotor (M) drives the rotor of CT2 to its null position, and at the same time drives the rotors of the output heading synchro transmitter and the magnetic compass detector CT (CT1).

At the same time that servomotor M is driving, CT1 is delivering an error signal to slaving amplifier (A1). The output of A1 supplies the slaving torquer so as to cause the gyro to process in the proper direction to align itself (and thus the gyro synchro transmitter) with the output from the magnetic compass transmitter.

The gyro processes at a slow rate (about 2° per minute), therefore if the system is far out of correspondence a relatively long period of time is required for synchronization. The system output may be synchronized with the output from the magnetic compass transmitter without waiting for the gyro to precess into alignment. This is done by turning the heading switch (which turns the rotor of the CDX) while observing the synchronization indicator. The synchronization indicator is effectively a zero center scale milliammeter connected in the slaving amplifier output circuit.

GYRO MODE.—During the gyro mode of operation, the slaving amplifier output is disconnected from the slaving torquer and a latitude compensating voltage applied in its place. The latitude compensating voltage is set manually by the latitude compensation control which is scaled in degrees of latitude. Setting the control to the local latitude applies the correct signal voltage to the slaving torquer so as to cause the gyro to precess at the proper rate and in the proper direction to cancel the apparent precession due to the earth's rotation.

AIRCRAFT AUTOMATIC PILOT SYSTEM

The aircraft automatic pilot (autopilot) system functions to maintain the desired heading and keep the aircraft level automatically during flight. Stabilizing, rate, and directional gyros are used with synchro pickoffs to sense and transmit aircraft roll, pitch, rate-of-turn, and yaw motions, and synchro servo loops operate the ailerons, elevator, and rudder to keep the aircraft on straight and level flight.

A simplified block diagram of an autopilot system is shown in figure 6-11. More elaborate systems (usually referred to as automatic flight control systems) are used in modern aircraft, however figure 6-11 is the basic system.

AILERON AND ELEVATOR CONTROL LOOPS

Roll and pitch data for the aileron and elevator control loops originates in the gyro horizon indicator (fig. 6-11). A vertical gyro provides the stable level reference and two synchro transmitters functioning as gyro pickoffs provide roll and pitch displacement signals to the stators of roll and pitch CTs (CT1 and CT3). The CTs supply error signal inputs to roll and pitch servoamplifiers (A1 and A2).

With the aircraft on level flight, roll and followup CTs (CT1 and CT2) are at null; there is no error signal input to roll servoamplifier A1; and the roll servoloop is at rest. Any movement of the aircraft in roll attitude causes a corresponding roll error signal to be developed by CT1 and fed to roll servoamplifier A1. Roll servomotor (M1) supplied by the output from A1, drives the aileron control surfaces from streamline to correct for the error, and at the same time drives the rotor of followup synchro transmitter CX1 which supplies the stator of followup synchro control transformer CT2.

The output of CT2 (which is 180° out of phase with CT1) is also fed to the input of servoamplifier A1. Thus when the CT1 and CT2 outputs become equal in magnitude, servomotor M1 stops driving the aileron control surfaces. As the control surfaces are now displaced from streamline, the aircraft starts moving back toward level flight thus causing the output of CT1 to start decreasing. This results in the CT2 output becoming the predominate signal, and as such, the servomotor now starts driving in the opposite direction restoring the aileron control surfaces to streamline. When the aircraft is back to a level atitude and the aileron control surfaces are back to streamline, the CT1 and CT2 outputs are again at null.

The elevator control loop includes CT3, CT4, A2, M2, and CX2. This loop functions in the

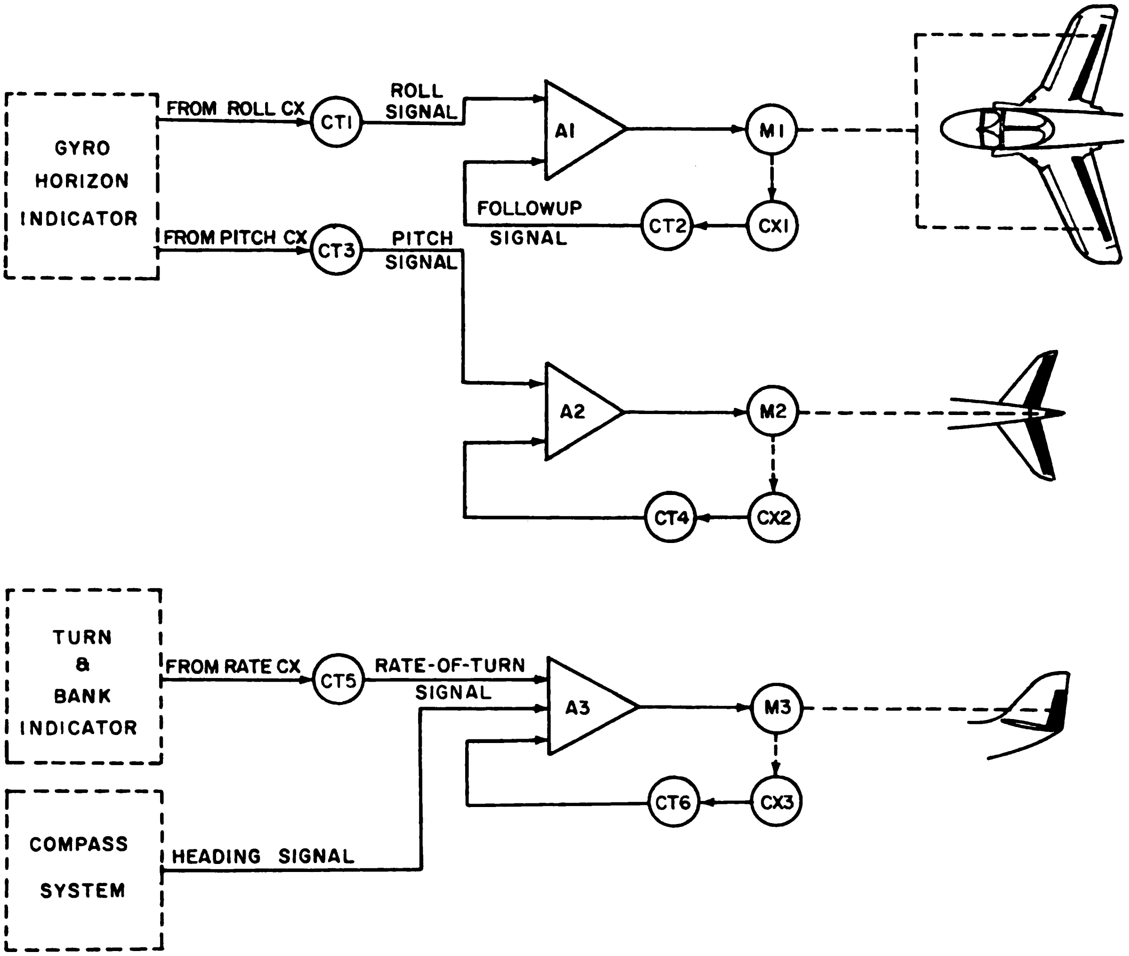

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Figure 6-11.—Simplified diagram of an aircraft autopilot system.

same manner as the aileron control loop to control the pitch atitude of the aircraft.

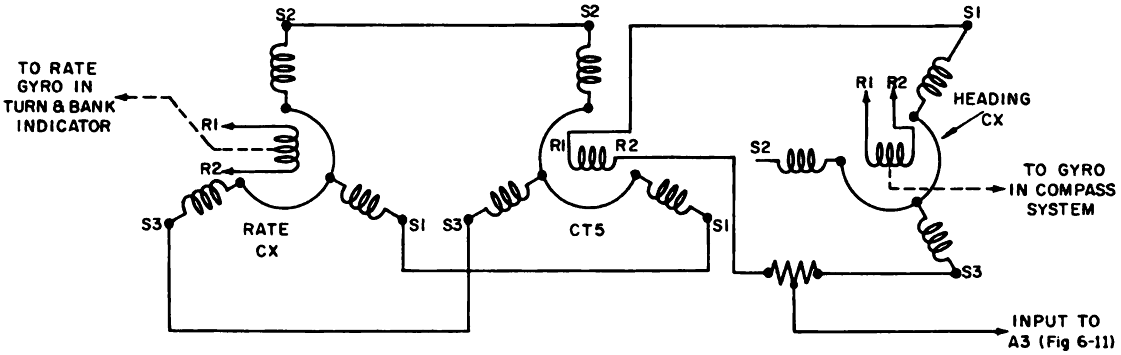
RUDDER CONTROL LOOP

The rudder control loop functions to control the aircraft rudder so as to keep the aircraft on a preset heading. The error signal input to the rudder servoamplifier (A3) is the sum of the heading signal from the compass system and the rate-of-turn signal from the turn and bank indicator, minus the followup signal (fig. 6-11).

A rate gyro in the turn and bank indicator uses a synchro transmitter as a pickoff to develop a signal proportional to the aircraft's rate of turn. This synchro signal is applied to the stator of the rate CT (CT5). The heading signal is provided by a synchro transmitter in the compass system.

As long as the aircraft is on the heading that it was set on when the autopilot system was engaged, there is no error signal input to rudder servoamplifier A3. If the aircraft departs from this heading however, the rate CX develops a synchro signal proportional to the aircraft's rate of turn, and the heading CX develops a signal that corresponds to the aircraft's displacement from the preset heading. The output from CT5 and the heading CX are summed and the resultant applied to the input of servoamplifier A3 as shown by the simplified schematic diagram (fig. 6-12).

Servomotor (M3) displaces the rudder from streamline so as to stop the turning of the air-



175.50
Figure 6-12.—Summing of rate-of-turn and heading signals.

craft, and also drives followup CX (CX3) to provide the followup signal. The followup signal is 180° out of phase with the resultant of the rate-of-turn and the heading signal and thus enables the servoloop to control the aircraft in the same manner as described for the aileron control loop.

INERTIAL NAVIGATION SYSTEMS

An inertial navigation system is a navigation system which (after initial conditions are set into the system) functions to continuously compute the latitude and longitude of a moving vehicle (such as a ship, aircraft, or missile) by sensing the vehicles accelerations. An inertial guidance system includes an inertial navigation system with the additional initial data and attitude and guidance controls necessary to guide the vehicle to a preset destination.

The heart of the inertial navigation system is an arrangement of accelerometers which will detect any change in vehicular motion. The accelerometers are arranged so as to sense accelerations in the North-South and East-West directions. These accelerations are doubly integrated with respect to time to obtain distance traveled.

FUNDAMENTALS OF INTEGRATION

Since the process of integration is so frequently used in navigation systems, a simplified explanation is given. It is used here to explain the relationship of acceleration to velocity and distance traveled. In inertial navigation, distance traveled is calculated from measured acceleration by first integrating acceleration with respect to time to find velocity, and then integrating velocity with respect to time to find distance traveled.

Velocity is defined as a rate of change of distances with respect to time, $V = \frac{ds}{dt}$. The familiar unit of miles/hour is the dimension of velocity. Acceleration is a physical phenomenon equal to the rate of change of velocity with respect to time, $a = \frac{dv}{dt}$. Because the area under the acceleration curve is proportional to velocity, if the mathematical process of integration is performed on the quantity acceleration, the result is velocity. Likewise, because the area under the velocity curve is proportional to distance if the mathematical process of integration is performed on the quantity velocity, the result is distance. Figure 6-13 illustrates the relationships of acceleration, velocity and distance.

In order to illustrate these relationships clearly, constant values of accelerations are chosen for each of the first four intervals (time 0 to time 4). Integrating the constant acceleration for time 0 to time 1 gives a velocity (V) which increases linearly. Velocity at the end of the first interval is actually computed by measuring the area under the acceleration curve (time 0 to time 1).

Recall that the fundamental formula for velocity is $V = at$; where V = Velocity, a = acceleration, and t = time. The precess of integration subdivides each interval shown in figure 6-13 into an infinite number of tiny intervals. Integration is, then, the process of adding, or

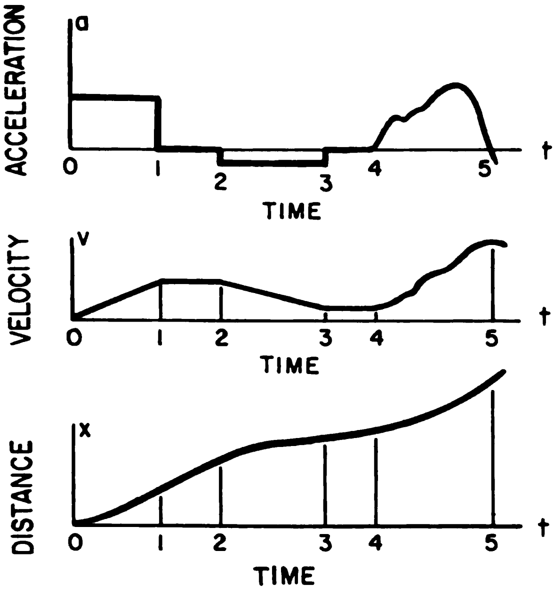


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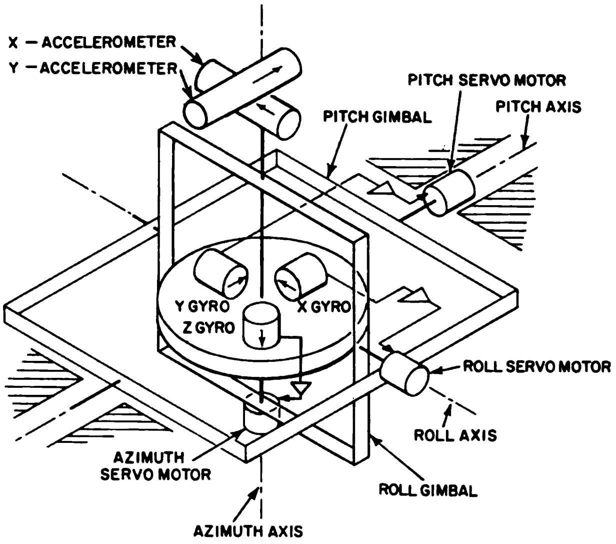
Figure 6-13.—Integration of acceleration to obtain velocity and distance.



162.55
Figure 6-14.—Stable platform with inertial components.

summing, an infinte number of incremental areas under a curve to obtain the total area. The velocity curve, therefore, is a plot of subtotals of the incremental areas under the acceleration curve.

In the second period (time 1 to time 2), the acceleration is zero, and the velocity remains constant. In the third period, there is a constant negative acceleration which reduces the velocity subtotals at a constant rate. In the fourth period, there is no acceleration and no change in velocity. In the fifth period, a random acceleration and its approximate integral, the velocity, are shown.

The distance curve is a plot of subtotals of the incremental areas under the velocity curve.

An example of integration is a d.c. motor driving a counter. If a voltage proportional to velocity is present, it could be used to drive the motor so that the speed of the motor would be proportional to velocity; and the number of revolutions or the counter reading would indicate distance traveled. Thus, velocity would be integrated to find distance.

The mathematical process of integration is discussed in more detail in Mathematics, Vol. 2, NavPers 10071-B. Electronic circuits that perform integration are discussed in Basic Electronics, NavPers 10087 (revised).

STABLE PLATFORM

To determine the position (latitude and longitude) of a moving vehicle at any point along its path, the accelerometers must be mounted in mutually perpendicular axes which continually maintain their relationship with some fixed reference point. In most inertial systems, the center of the earth is used as the fixed reference point.

When the center of the earth is used as the reference, all vehicular motion is determined on the basis of accelerometer outputs with reference to that point. In this type of inertial system it becomes necessary to stabilize the accelerometer axes so that they always maintain their same relationships with the earth's center.

In order to understand how the stable platform functions to maintain the reference system, a simple sketch of a platform with gimbals, gyros, accelerometers, and servomotors is illustrated in figure 6-14.

Stabilization is accomplished by mounting the accelerometers and gyros on the platform such that the input axis of the gyros are perpendicular to the sensitive axis of the accelerometers. By referring to figure 6-14 it can be seen with the gyros on the stable element that: (1) the heading gimbal axis is always aligned to the Z gyro; (2) the roll gimbal axis is aligned to the X and Y gyros as a function of heading; (3) the pitch gimbal is aligned to the X and Y gyros as a function of heading and roll and to the Z gyro as a function of roll. Any motion about the input axis of the gyro (due to roll, pitch or yaw) causes the gyro to precess about its output axis. The gyro pickoff measures this precession and sends an actuating signal to the gimbal servomotors which in turn drive the platform relative to the vehicle, in a direction opposite to the direction of the ship's motion. The platform is driven until the gyro pickoff signal is zero. The platform therefore moves with respect to the ship but remains stationary or aligned with respect to the reference plane of direction.

Any vector, such as acceleration, can be resolved into two right angle components. Since distance north-south, along a meridian of longitude, can be related to degree of latitude; and distance east-west, along a line of latitude, can be related to degrees of longitude, two accelerometers are mounted on the platform so that their sensitive axes are mutually perpendicular. One, the "X" accelerometer, is always aligned north and the other, the "Y" accelerometer, is always aligned east.

In figure 6-14 any ship's motion about its roll axis while headed north, will result in the X gyro sensing this rotation causing a signal to drive the platform with respect to the ship by way of the roll servomotor. Pitching motions will be sensed by the Y gyro which will cause the pitch servomotor to drive, keeping the platform leveled. Figure 6-14 shows electrical connections from the X gyro to the roll servomotor which is satisfactory for a ship headed 000 degrees, but when the ship is headed 090 degrees a roll position will be sensed by the Y gyro which must cause the roll servomotor to drive. However, as seen in the diagram, the Y gyro feeds the pitch servomotor. When on an intercardinal heading both the X and Y gyro will sense a roll motion that only the roll servomotor need drive to maintain stabilization. There must be a circuit which will combine the precessional signals and cause the proper servomotor to drive. This circuit is known as the stabilization loop.

Figure 6-15 is a simplified schematic diagram of the stabilization loop. Note that the gyro pickoffs feed resolvers, and that these resolvers are positioned according to the angles of heading and roll. The heading and roll resolvers are usually mounted on the gimbals, and are driven whenever the particular gimbals are driven by their servomotors.

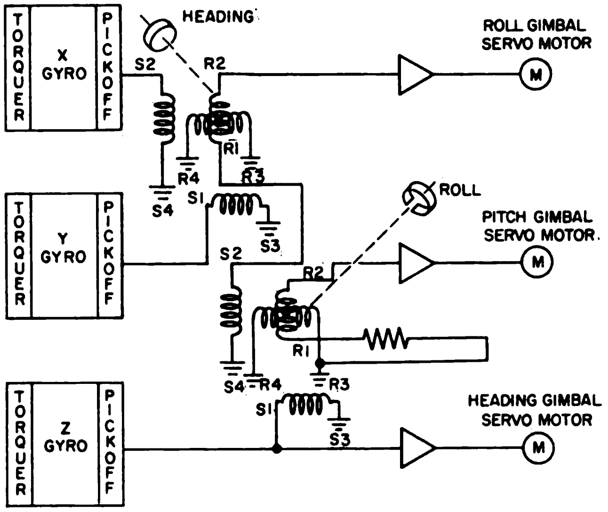


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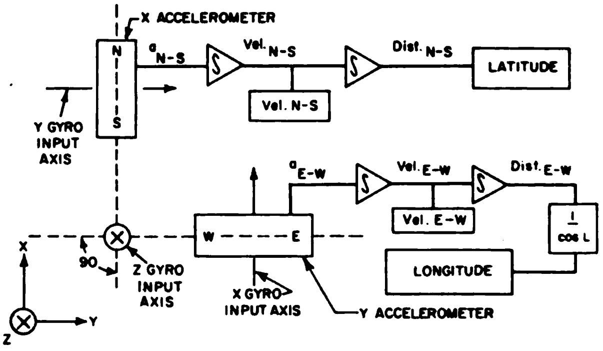
Figure 6-15.—Three-gimbal stabilization loop.

COMPUTING LATITUDE AND LONGITUDE

Figure 6-16 shows in block diagram form how the system computes latitude and longitude. The X direction is defined as an axis along the north-south direction and tangent to the surface of the earth. The Y axis is along the



162.56
Figure 6-16.—Block diagram sequence for computing latitude and longitude.

east-west tangent to the earth. The X accelerometer senses accelerations in a north-south direction. Its output is used to compute velocity north and distance north which is related to latitude. The Y gyro senses any rotation of the accelerometer's sensitive axis from its aligned position. The Y accelerometer senses acceleration east-west. From this output is computed velocity and distance east-west which is related to longitude by the ratio 1/cos latitude, (at the equator, one mile equals one minute of longitude. While at 45 degrees of latitude, one mile equals 1.4 minutes of longitude).

The X gyro senses rotation of the Y accelerometer from its aligned position and the Z gyro has its input axis aligned perpendicular to the plane containing the X and Y axes. The axis is parallel to the local gravity vector. It is precessed whenever the platform moves in azimuth from its northeast orientation.

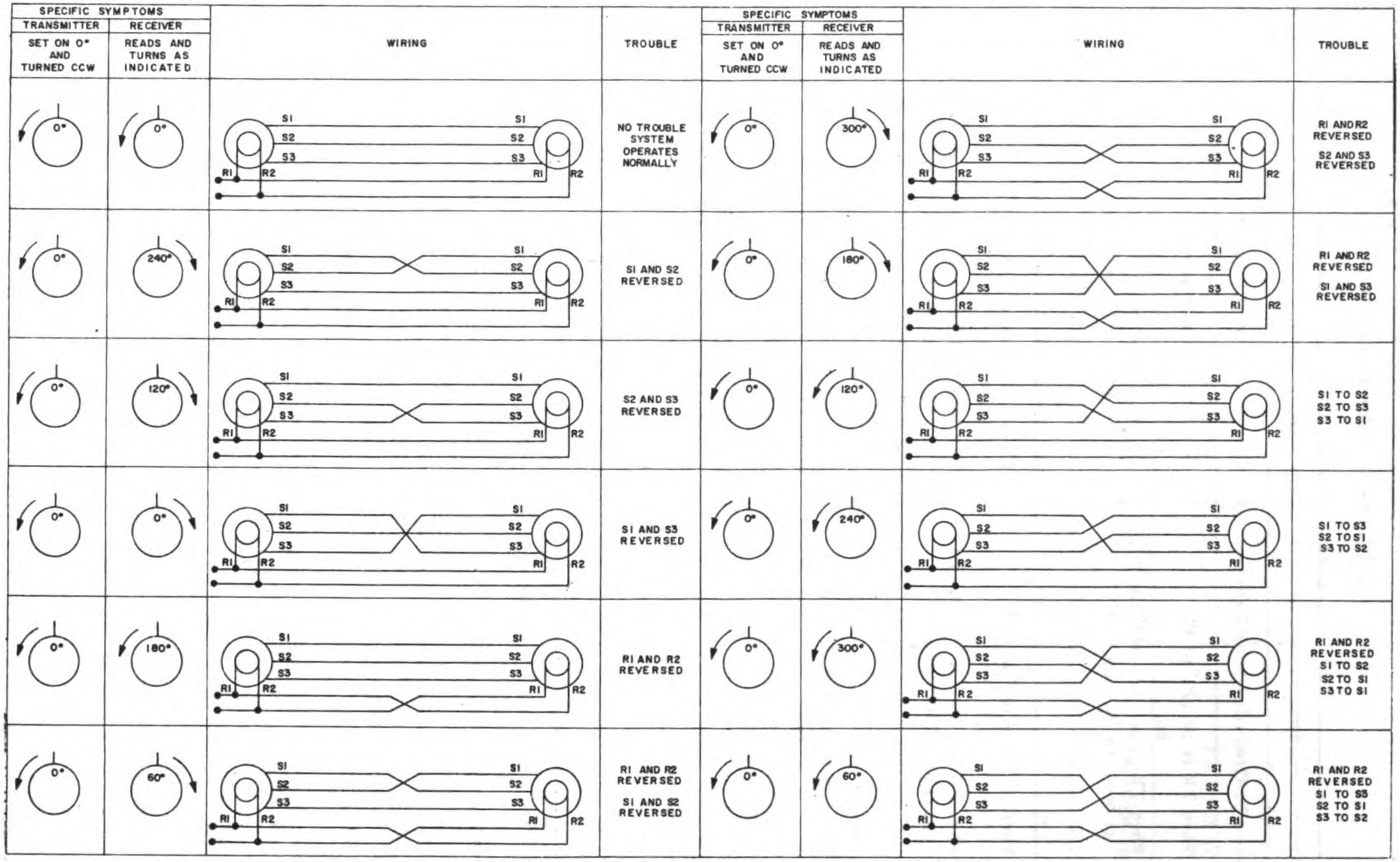
Since the three gyro input axes are mutually perpendicular no rotational motion of the platform from its aligned position will escape being sensed by one or more gyros.

Many of the problems associated with this type of inertial navigation system have not been discussed in this brief discussion. Among these are such things as the effects of Schuler Tuning, gyro drift, accelerometer error, platform misalignment and computer error.

APPENDIX I

SYNCHRO TROUBLES

SYNCHRO TROUBLES



SPECIFIC SYMPTOMS TRANSMITTER SET ON 0° AND TURNED CCW	SPECIFIC SYMPTOMS RECEIVER READS AND TURNS AS INDICATED	WIRING	TROUBLE
0°	0°	S1 S2 S3 R1 R2	NO TROUBLE SYSTEM OPERATES NORMALLY
0°	240°	S1 S2 S3 R1 R2	S1 AND S2 REVERSED
0°	120°	S1 S2 S3 R1 R2	S2 AND S3 REVERSED
0°	0°	S1 S2 S3 R1 R2	S1 AND S3 REVERSED
0°	180°	S1 S2 S3 R1 R2	R1 AND R2 REVERSED
0°	60°	S1 S2 S3 R1 R2	R1 AND R2 REVERSED S1 AND S2 REVERSED
0°	300°	S1 S2 S3 R1 R2	R1 AND R2 REVERSED S2 AND S3 REVERSED
0°	180°	S1 S2 S3 R1 R2	R1 AND R2 REVERSED S1 AND S3 REVERSED
0°	120°	S1 S2 S3 R1 R2	S1 TO S2 S2 TO S3 S3 TO S1
0°	240°	S1 S2 S3 R1 R2	S1 TO S3 S2 TO S1 S3 TO S2
0°	300°	S1 S2 S3 R1 R2	R1 AND R2 REVERSED S1 TO S2 S2 TO S1 S3 TO S1
0°	60°	S1 S2 S3 R1 R2	R1 AND R2 REVERSED S1 TO S3 S2 TO S1 S3 TO S2

1.118
Figure A-1.—Reversed and interchanged connections.

175.51

Table A-1.—Open or shorted stator.

SYMPTOMS		TROUBLE
SETTING OR CONDITIONS	INDICATION	
When TX is on 120° or 300° but When TX is between 340° and 80°, or between 160° and 260°	Overload Indicator goes out and TR reads correctly Overload Indicator lights, units get hot and hum, and TR stays on 120° or 300°, or may swing suddenly from one point to the other	Stator circuit shorted from S1 to S2
When TX is on 60° or 240° but When TX is between 280° and 20°, or between 100° and 200°	Overload Indicator goes out and TR reads correctly Overload Indicator lights, units get hot and hum, and TR stays on 60° or 240° or may swing suddenly from one point to the other	Stator circuit shorted from S2 to S3
When TX is on 0° or 180° but When TX is between 40° and 140°, or between 220° and 320°	Overload Indicator goes out and TR reads correctly Overload Indicator lights, units get hot and hum, and TR stays on 0° or 180°, or may swing suddenly from one point to the other	Stator circuit shorted from S1 to S3
	Overload Indicator on continuously, both units get very hot and hum, and TR does not follow at all or spins	All three stator leads shorted together
When TX is on 150° or 330° and When TX is held on 0°	TR reverses or stalls and Overload Indicator lights TR moves between 300° and 0° in a jerky or erratic manner	S1 stator circuit open
When TX is on 90° or 270° and When TX is held on 0°	TR reverses or stalls and Overload Indicator lights TR moves to 0° or 180°, with fairly normal torque	S2 stator circuit open
When TX is on 30° or 210° and When TX is held on 0°	TR reverses or stalls and Overload Indicator lights TR moves between 0° and 60° in a jerky or erratic manner	S3 stator circuit open
When TX is set at 0°, and then moved smoothly counterclockwise	TR does not follow, no Overload Indication, no hum or overheating	Two or three stator leads open or both rotor circuits open

175.52

Table A-2.—Open or shorted rotor.

Preliminary Action: Set TX to 0° and turn rotor smoothly counterclockwise.

SYMPTOMS	TROUBLE
TR turns counterclockwise from 0 to 180° in a jerky or erratic manner, and gets hot	TX rotor open
TR turns counterclockwise from 0 or 180° in a jerky or erratic manner. TX gets hot	TR rotor open
TR turns counterclockwise from 90 or 270°, torque is about normal, motor gets hot, and TX fuses blow	TX rotor shorted
TR turns counterclockwise from 90 or 270°, torque is about normal, TX gets hot, and TR fuses blow	TR rotor shorted

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